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PAPERS RELATED TO GASOLINE SUPPLY, MISFUELING, AND ENVIRONMENTAL AIR QUALITY FOR THE SUMMER OF 1979

D. Dacy
P. Cutchis
F. Giertz
R. Kuenne
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October 1979

Prepared for
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IDA

INSTITUTE FOR DEFENSE ANALYSES
PROGRAM ANALYSIS DIVISION

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This volume contains nine back-up essays to the study, "Analysis of Options to Limit Air Quality Degradation Due to Misuse of Leaded Gasoline in Cars Equipped with Catalytic Converters," IDA P-1426. Thus, the essays pertain to the problem of "misfueling" which was a prominent feature of the gasoline shortage in the summer of 1979.

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FOREWORD

Each entry in this volume was written as a supporting paper to the IDA study for the Environmental Protection Agency, Contract No. 68-01-5150, entitled *Analysis of Options to Limit Air Quality Degradation Due to Misuse of Leaded Gasoline in Cars Equipped with Catalytic Converters*, and published as IDA Paper P-1426. These papers were a quick response to a problem that appeared suddenly in the late spring of 1979. In brief, the problem was a shortage of gasoline (particularly unleaded gasoline) that arose from a number of causes, most notably the curtailment of oil exports from Iran. The major manifestations of the shortage were queueing for gasoline, rapid run up in prices, compression of the price differential between leaded and unleaded gasoline and compression of prices charged at self-service and full-service stations. The shortage virtually disappeared in August 1979.

There may be some minor inconsistencies in the papers presented here. No major attempt has been made to remove them. Also, because the papers were rapidly written, there is no claim that any would be written at the present time as it was originally. The authors hope that the basic ideas presented are worthwhile and clear. IDA has published them as a companion to IDA P-1426 because a reader of that study might be interested in more detail than presented there.

AN ECONOMIC EVALUATION OF THE CURRENT SUPPLY SITUATION FOR UNLEADED GASOLINE*

Henry Steele

1. INTRODUCTION AND SUMMARY

This study stems from a request for evaluation of the factors responsible for the current shortage of unleaded gasoline. This request was motivated in part by concern in some government quarters that oil companies, on purely economic grounds of maintaining desired rates of return on investment, might be individually refraining from making what would appear to be demand-justified investments in unleaded gasoline refining capacity: the concern being that if unleaded gasoline is not available in the required volumes, some motorists will have to substitute leaded gasoline. This substitution, of course, deactivates catalytic converters in automotive engines and thus increases the emission of air pollutants.

This study attempts a very brief investigation of four issues. The first issue is whether or not there is in fact an economic disincentive to invest in the added octane capacity necessary to increase unleaded gasoline yields, rather than to stay with existing capacity in unleaded gasoline production. Although oil companies do not release data from their own economic studies of profitability of octane capacity investments, a review of existing gasoline price control regulations, together with some first-approximation estimates of the profitability of new octane capacity investment projects, indicates that under present regulations returns to such investments appear to be negative.

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*This paper was completed in June 1979.

The second issue is whether or not oil companies can be expected to make such investments in order to protect their established market shares in gasoline sales, even if under present conditions expected returns are negative for the additional investments. Economic theory of market organization suggests that rival firms in competitive markets feel strongly motivated to take the steps necessary to prevent their market shares from declining, particularly for their main products. Interviews with refining, supply, and marketing department personnel in several major oil companies with offices in the Houston area support the view that market share and its preservation is important to major oil companies, and that, in general, the larger the company the more likely it is to make the necessary investments, hoping that regulatory conditions will change in the future so that the decision will prove to be justified on the basis of profit. Significant octane capacity investments have been made in the last four years, and oil companies generally appear to have plans to continue to alter their refinery yield patterns in order to keep the leaded/unleaded gasoline output mix consistent with the market demand for these two fuels (as determined chiefly by the age distribution of the stock of motor vehicles).

It appears, however, that the company personnel responsible for making these investment decisions are finding it increasingly difficult to predict with confidence the eventual decontrol of gasoline prices. As a result, it takes longer for a favorable decision to be made, and companies try to adopt loss-minimizing strategies within regulatory constraints. These strategies generally involve the substitution of primarily short-run expedients (such as "debottlenecking"--through, for example, modification of the operating conditions of existing facilities, or by obtaining intermediate inputs by purchase rather than by producing them directly) where the added cost incurred can be at least partially recovered under cost recovery pricing formulas now in use. Because under long-run programs of building new facilities the costs cannot be adequately recovered under regulation, the effect of the regulations is to distort activities toward short-run expedients for octane improvement rather than toward long run investment in new octane capacity.

The third issue is to examine the present shortage of unleaded gasoline in the context of the appropriate total world petroleum market. The current situation is fundamentally one of a "shortfall" of crude oil supply in world markets rather than merely one of a shortage of unleaded gasoline capacity per se. Major oil companies in the Houston area appear reasonably confident that the oil industry as a whole will increase the share of unleaded gasoline in the total gasoline pool from about 38 percent as of the end of 1978 to about 45 percent as of the end of 1979. The costs of moving to 80 percent unleaded by 1985 are estimated at $2 billion to $5 billion. With reference to supply, however, a tight situation will exist for both the unleaded and the leaded gasoline markets, as well as for other refined products markets generally. The reduction in oil imports which has taken place since the Iranian revolution was not experienced as a severe supply shortage in the first quarter of 1979 since (1) there was a time lag of more than a month between the cessation of exports and the cessation of imports owing to the long transit time of oil shipped by sea, and (2) the reduction of refined products inventories, which substitutes stored products for currently produced ones. But in the second quarter of 1979 the industry now faces not only the problem of absorbing the decline in imports which has persisted ever since the Iranian re-entry, but also the problem of rebuilding inventories of refined products---particularly heating oil and other middle distillates--during a season when the demand for motor gasoline reaches its peak.

Demand factors also seem to be partly responsible for the occasionally greater shortages of unleaded than of leaded gasoline. It appears that the Iranian crisis induced many owners of "gas guzzlers" to retire their cars earlier than anticipated, leading to an increased demand for unleaded gasoline, particularly on the Pacific Coast, where used car prices for such relatively late model automobiles have recently declined sharply. On the other hand, many of the newer cars do not perform adequately with available grades of unleaded gasoline, so that switching into leaded gasoline may occur for reasons of fuel quality, even if unleaded supplies are not deficient. Serving further to complicate matters is the uneven regional incidence of demand increases for gasoline. Although the 1978-1979 increase in unleaded gasoline demand for the nation as a whole appears to have been roughly what was anticipated, the increase in the Pacific Coast region is about four times as great as in the rest of the country, leading to regional gasoline supply shortages.

In summary, it seems to be the judgment of those in the oil industry that the aftermath of the Iranian revolution is the most significant factor in the current shortfall of crude oil. About 80 percent of the shortfall is due to the inability of Iran to restore past production rates, coupled with the unwillingness of other OPEC members to make up the existing reduction in Iranian exports. Another 10 percent is due to declining U.S. production, the replacement of which would ordinarily call for increasing oil imports above the 1978 level. The other 10 percent would be attributable to other factors, among them the opportunistically high spot prices charged by OPEC members for added exports, coupled with the suggestions by the U.S. government (apparently withdrawn in recent weeks) that U.S. companies should not pay spot prices above $20 per barrel unless they wished to face the possibility that price regulators would not allow a pass-through of higher crude oil costs in the cost-justification formulas used to price gasoline.

The fourth issue involves the controversy over what measures should be adopted to prevent switching by new car owners from unleaded to leaded fuel. For some new car owners, leaded fuel represents both a better quality and a lower price product. Several possible remedies are suggested: improve the quality of unleaded gasoline; raise the price of leaded gasoline; and lower the price of unleaded gasoline. It would appear that reducing the quality differential would be more efficient in the long run while reducing the price differential might either help or hurt depending upon the method chosen. Reducing or eliminating the present price differential in favor of leaded gasoline by raising the price of leaded gasoline (through a pollution tax, for example, based on lead content) would help, while reducing the price of unleaded gasoline would hurt. Although this issue is not a major focus of this paper, some discussion of this topic is included in view of its relevance to the earlier analysis.

2. ECONOMIC INCENTIVES AND DISINCENTIVES FOR INVESTMENT IN INCREASING CAPACITY OF REFINERIES TO PRODUCE UNLEADED GASOLINE

It is impossible to discuss adequately the economics of new refinery investment in either leaded or unleaded gasoline without going into the minute details of refinery technology--which are beyond the scope of this paper and of the technological expertise of its author. Nevertheless, a brief primer on the mechanics of gasoline production flows in a refinery is essential. Figure 1 presents in schematic form the input-output flows between the crude oil stream and the gasoline yield, in a highly simplified manner. The crude oil enters from the far left, and is subjected to thermal distillation in unit A, where simple heating separates the more volatile components or fractions of the crude oil input from the less volatile fractions. Those components which have the lowest vaporization temperatures are called light virgin napthas (LVN) and may constitute about 10 percent of the crude oil stream. The LVN stream which has an octane rating of about 70, when rated by averaging the research octane rating and the motor octane rating (i.e., defining the octane rating as (r + m)/2, as is consistently done in this paper), is subjected to isomerization in facility B and the resulting yield is a much higher quality gasoline with an octane rating of about 90. Isomerization produces no by-products and causes no appreciable volume loss or gain. Approximately 10 percent of the total crude oil stream is thus converted to 90 octane gasoline by isomerization of the LVN stream.

About 15 percent of the crude oil stream, referred to as heavy virgin naptha (HVN), vaporizes at a somewhat higher range

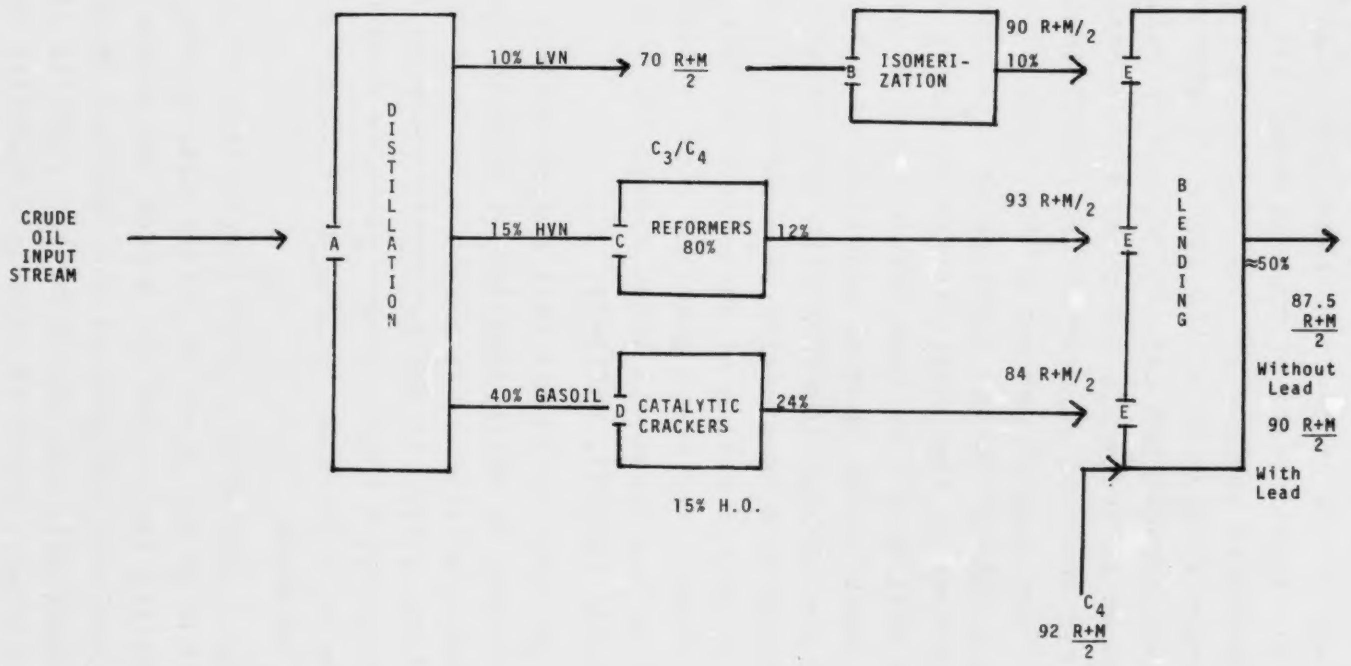

Figure 1. SCHEMATIC DIAGRAM OF GASOLINE PRODUCTION IN A REFINERY

of temperatures. The HVN stream is fed into a reforming unit (c) which converts about 80 percent of the HVN, or 12 percent of the volume of the crude oil stream, into high quality gasoline with an octane rating of approximately 93. Other outputs from the reformers include volumes of propane (C_3) and butane (C_4). Another 40 percent of the crude oil stream has vaporization points between 550 and 1050°F, and is called gasoil. The less volatile stream is fed to catalytic cracking units (D) which convert about 60 percent of the gasoil input into 84 octane gasoline. Thus some 24 percent of the original crude oil stream is converted into 84 octane gasoline by catalytic cracking. The other 40 percent of the gasoil stream is generally converted into distillate fuel oils. We thus obtain about 46 percent of the crude oil input in the form of gasolines of various octane ratings which are blended together with such other inputs as butane (itself having an octane rating of about 92) to yield a gasoline pool with an octane rating of about 87.5 without lead, or 90 with lead added. The total gasoline pool is thus approximately 44 percent of the crude oil input stream for this particular, and presumably typical, refinery.

This provides of course only the sketchiest of descriptions of the processes by which gasoline is produced in a modern refinery. Many variations are possible, such as the introduction of part of the output of the catalytic crackers into the reformers in order to produce higher octane gasoline from the reformers at the expense of a lower net output of 84 octane gasoline from the catalytic crackers.

For an engine with a given compression ratio, the higher the octane rating of the gasoline before adding lead, the less the need for adding lead. But the higher the octane goal of the unleaded gasoline, the greater the "processing severity" imposed upon the crude oil, and the lower the quantity yield from the crude oil stream. There is clearly a quantity vs. quality tradeoff involved in octane enhancement. Lead and crude oil are substitutes in achieving a given octane rating; the less lead used, the more crude oil is required per gallon of gasoline produced.

Let us now look at some of the general alternatives available to refiners who wish to provide higher octane ratings. First, other things remaining equal, one could simply add lead. Second, other things again remaining equal, one could invest in the construction of an isomerization unit for a refinery which previously lacked such a unit, and merely fed the light virgin naphtha stream directly into the gasoline blending pool. Third, one could add more reforming capacity and at the same time add more crude oil input, feeding some of the naphtha output from the catalytic crackers into the reformers. Suppose, for the sake of a very crude calculation, that a refinery's reforming capacity is doubled and that five-eighths of the 84 octane gasoline output stream from the catalytic crackers is fed into the reformers. If this input is processed into 93 octane gasoline at an 80 percent of volume ratio by the reformers, then 24 percent of the crude oil stream is converted into 93 octane gasoline and only 12 percent is left as the net yield of 84 octane gasoline from the catalytic crackers. Thus the total gasoline volume yield is reduced from 46 percent of the crude oil stream (10 from isomerization plus 12 from reforming plus 24 from catalytic cracking) to 43 percent (10 from isomerization plus 24 from reforming plus 9 from catalytic cracking). If total gasoline volumes are to be maintained, the crude oil input stream must be increased by 7 percent (46/43 = 1.07). Fourth, one could purchase higher octane blending stocks and introduce these into the gasoline pool, with processing facilities and crude oil inputs held constant.

In the absence of price regulation, if market demand for unleaded gasoline were to rise due to increases in the population of motor vehicles designed to use this fuel, companies would logically select some cost-minimizing combination of these and other methods to produce enough unleaded gasoline to meet rising demands. To meet anticipated long run growth of demand, investment in new facilities would be optimal; to meet short run fluctuations in demand, changing the operating characteristics of process facilities, or purchasing more blending stocks might be justified even though operating costs might be higher than if the same capacity could be provided for by new investment. Given the existence of price regulation, however, characteristics of the regulatory system distort the choice between alternative methods in the direction of selecting those expedients which maximize the gains, or minimize the losses, from regulated operations rather than choosing those which minimize long-run costs.

After having grossly oversimplified the technology of gasoline refining in the interest of providing a description of manageable length, let us now for the same purpose strive to simplify the economics of regulation of refined products prices. Existing regulations derive fundamentally from 1975 legislation which fixed the maximum cost-justified prices for petroleum products by reference to product price levels as of May 1973, with adjustments for "pass-throughs" of certain categories of increased costs since that time, such as crude oil purchase costs. If no input costs had increased since May 1973, then the profit margin permitted under price regulation in all subsequent years would be frozen at the number of cents per gallon received in May 1973, and the price would remain similarly frozen. If the costs of all purchased inputs had increased in such a way as to permit their direct pass through in the form of higher prices, then the profit margin would still remain at the May 1973 level in terms of cents per gallon, although profit as a percent of the sales price would decline. Such an outcome would also imply some decline in profit as a rate of return on investment, since higher costs for the working capital embodied in inventories of higher-priced crude oil, work in process, and finished products in storage, would involve some increase in the total investment cost of producing a gallon of refined products. But if investment costs for process facilities increase, whether for reasons of price inflation, technological change, or for other causes, then the fixed per gallon profit margin as of May 1973 cannot provide the same rate of return on new investments in later years as it provided for existing investments as of 1973. The problem is further compounded if under the regulations certain categories of increased costs cannot be passed on in full or in part as recognized components of the cost basis for price "justification."

Since price inflation, changing market conditions in the supply and construction industries, changing interest rates and expectations, and more forbidding environmental and other regulatory climates have in fact increased the cost of new refinery construction by a factor of two or three since 1973, the same margin in cents per barrel now provides only about one-third to one-half the rate of return on current new investment relative to 1973 investment. Thus all refinery investment is discouraged. But certain features of price control regulations act additionally to discourage new investment in octane capacity.

In general, increased costs can be passed through in either of two categories: (1) fuel costs; and (2) "non-product" costs. Fuel costs are primarily crude oil costs, although purchased blending stocks introduced into the gasoline pool would also qualify in this general category. "Non-product costs" are essentially non-fuel operating costs, with the inclusion of depreciation of new equipment on a straight-line basis. As far as the gasoline pool is concerned, crude oil costs can be charged against gasoline production to the extent that the volume of gasoline produced is a given fraction of the crude oil volume required as refinery input. If half of the crude input is converted into gasoline, 50 percent of the crude oil costs can be charged against gasoline. If purchased refined products or unfinished oils are used as blending stocks in the gasoline pool, 100 percent of their costs can be charged against gasoline for purposes of computing the maximum cost-justified price. Refinery non-product costs such as operating costs other than fuel can also be charged against gasoline sales to the extent that gasoline output is some percentage of total crude oil input. Marketing non-product costs (transportation from the refinery, and subsequent distribution and sales costs) can be divided between gasoline and other products on the basis of the ratio of gasoline sales to total sales of all refined products.

Originally, all refined petroleum products (excluding such specialty items as asphalt) were price-controlled when the basic legislation went into effect in 1975. The price regulation scheme was inherently inefficient from the economist's point of view since it contemplated the fixing of maximum sales prices on the basis of the assumption that the average cost per gallon of producing each refined product was essentially the same. But efficient pricing requires the equating of marginal costs with marginal revenues for each product, rather than the mere relating of an imputed average cost to whatever demand conditions happen to prevail in a variety of different refined product markets. The cost of gasoline production (particularly higher octane gasoline) is higher than the cost of producing other refined products, such as residual fuel oil, as linear programming studies of the marginal costs of different refinery output mixes have repeatedly shown. One major difficulty with cost-based regulation is therefore that it entirely ignores the demand side of the market. But even as far as costs are concerned, gasoline and other more highly refined products are under priced while less intensely refined products are overpriced. Thus, assuming relatively neutral demand conditions among different products, the maximum cost-justified price available for gasoline under regulation would be lower than the competitive price, while maximum cost-justified regulated prices for less refined products would be above competitive levels. But, while sales can be mandated at less than competitive prices since producers are regulated and their facilities are in a sense hostages within some relevant time horizon, sales cannot be forced at more than competitive prices since consumers are not similarly regulated with regard to their preferences and demands. Thus under regulation it was not necessarily possible for all of the costs incurred by refiners to be recovered from allowable prices due to this asymmetry in the effect of the regulation on producers and consumers. Sellers must make the best of a low maximum price, at least within some short or intermediate run period, while the decreeing of a maximum price above the competitive level does not permit a competitive industry to obtain that theoretical maximum price. It is true that during an emergency period when supply is so tight relative to demand that all cost-based regulated prices are below what each market will bear, all costs can be recovered--and, of course, it is only during such a short run emergency period that there is a strong rationale for price controls of a temporary nature in an ordinarily price competitive industry. But when supplies are reasonably adequate for all products, at least some regulated prices will be above market prices and total costs therefore cannot be recovered.

Seasonality of demand is another area neglected under price regulation. Under competitive conditions the prices of many refined products will fluctuate seasonally as demand varies, with heating oil sales highest in winter and gasoline sales highest in summer periods. Current production will not necessarily vary precisely with current demand since the building up and reduction of inventories of products stored in anticipation of peak seasonal demands will allow sales in a given week or month to be greater or less than output, in proportion to inventory changes. But carrying inventories has its own costs, so supply and demand in a competitive market would combine to produce higher prices for seasonally variable fuels during the period of their peak market demands. Under regulation there is no such seasonal variation permitted in prices. Thus, the price variation necessary to allow for economics of cost-minimizing storage and distribution systems for each fuel with fluctuating demand is lacking, and other things being equal, refiners would have no price incentive to incur storage and other distribution costs necessary for the efficient marketing of these products. While this additional inefficiency of price regulation would appear to add another burden to the others already placed on resource allocation in the petroleum industry, other regulations tend to make the seasonal variation in the demand for some petroleum products a factor mitigating the general inability of refiners to cover all costs of operation during normal times.

To begin with the example of heating oil, the share of total refining costs allocated to this product would be about the same throughout the year on a per-gallon basis, but the market price under competition would vary. Since allocated processing costs (average cost basis) might be relatively high compared with actual processing costs (true marginal cost basis) the maximum cost-justified price for heating oil under regulation might be above the actual market price during most of the year, being reached or surpassed only during the period of peak seasonal demand for this product. The regulations were arranged so that if the market price is less than the allowed recovery price on a certain volume of sales during a certain period, then the unrecovered costs on that product are put in a so-called "bank" for heating oil, and as long as the market price is below the allowed recovery price the size of these "banked costs" for a particular product increases. During the peak heating season prices may (subject to some restrictions) be allowed to rise to competitive levels, with the difference between the now higher market price and the now lower allowed cost recovery price being taken out of the heating oil cost bank. The same processes would also apply to the other fuels with seasonally variable demand, such as gasoline, where the banked costs would tend to rise in the winter and decline in the summer. But the major source of variation in costs banked for other products than gasoline was the regulation permitting that banked costs accumulated in such fuels as distillate and residual fuel oils could be transferred to, or "rolled into" the gasoline cost bank. The aggregate of all banked costs generally rose in the winter and declined in the summer, but did not decline all the way to zero. The gasoline bank would ordinarily be quite small since refining costs were underallocated to gasoline, while gasoline demand was relatively price inelastic, such that a moderately reduced gasoline supply (which the regulations themselves tended to create) would command an enhanced price. But with costs underallocated to gasoline, actual market prices were seldom below maximum cost-justified prices. A low or negative bank in gasoline could be compensated for by rolling of banked costs for other fuels which were allocated a higher than actual share of total refining costs, and whose product demands might be less price inelastic. Thus the system of "banking" and "rolling in" costs came to provide some relief from the general price regulatory scheme which ignored supply and demand conditions for individual products, substituted average costs for marginal costs, and made no provision for explicitly seasonal variations in prices.

This system might not have been intolerable from the gasoline marketing standpoint as long as all refined products were price controlled, but when some products began to be decontrolled, beginning in 1976 with residual fuel oil, it was no longer possible to build up a bank of unrecovered costs which could be rolled into the gasoline bank. Under decontrol the product naturally has no maximum allowable recovery price, so market prices can never be less than a nonexistent reference price. Thus if a refinery produces 50 percent gasoline, but if the actual refining costs for gasoline are 70 percent of total refinery costs, under regulation only 50 percent of total costs can be passed through for cost-justified pricing purposes, and there is no way that all or any part of the other 20 percent can eventually be rolled in from the cost banks for other products.

As refined products were decontrolled one by one, gasoline prices tended to fall since the cost banks available for roll-in disappeared. This decline in gasoline prices was not due to market forces but simply due to the change in the regulatory system. If an adequate supply outlook for fuels other than gasoline develops, leaving actual market prices below cost-justified prices for these fuels, decontrol can occur since existing controls are not having any impact on the availability of these fuels. But with their cost banks eliminated, the cost-justified maximum price for gasoline declines, a factor which tends to reduce supply, increase amounts demanded, and create possible shortages in the gasoline market.

The decontrol of other fuels therefore reduced the price incentives for producing gasoline, but, given the greater costs involved in unleaded gasoline, differentially reduced the incentives for producing unleaded relative to leaded gasoline. In order at least partially to compensate gasoline producers for the loss of banked costs, the gasoline price control regulations were amended, effective as of March 1, 1979, to introduce a so-called "tilt" phenomenon into computed gasoline costs. The economic rationale, if one is imputed, would be to bring attributed average costs closer to actual marginal costs of gasoline production by recognizing that the cost of gasoline production in a refinery is more than proportional to the share of gasoline output in the total product streams. In administrative terms, however, the function of "tilt" was to simulate the average transfer of banked costs achieved during the period of price control for other fuels. Specifically, tilt permits a ten percent increase in the amount of crude oil costs which can be charged against gasoline production. (In this regard it is interesting that the oil companies argued for 15 percent, on engineering grounds, but did not prevail.)

For example, prior to tilt, if a refinery's gasoline output was 45 percent by volume of its crude oil input, 45 percent of the crude oil cost could be charged against gasoline costs. With tilt, the ratio became 49.5 percent (.45 x 1.1). The tilt on non-product costs is non-linear and the percentage skewing of recoverable costs varies with the percent of gasoline produced. If there is no gasoline output there is of course no skewing, and if all of the input is converted to gasoline there is similarly no skewing. In between these extremes, the percentage of skewing at first increases and then declines as the share of gasoline in the product stream increases. For a refinery producing 45 percent gasoline, for example, the skewing factor is such as to permit 70 percent of the non-product costs to be charged against the gasoline pool.

By early 1979 gasoline returns had fallen well below those received a year or more earlier under the banked cost transfer scheme. Tilt definitely improved the situation after March 1, favorably affecting the economics of gasoline production from existing facilities. Table 1 shows a very rough computation based on average industry experience for a typical large refinery with an output of about 200,000 barrels per day of all refined products. In this computation costs are not allocated among different products; instead, an average profit on all products as a percent of the sales dollar received for all such products is computed. Available data suggests that for a refinery of this type fuel costs are about 5/6 of total revenue, leaving a so-called gross profit margin of about 16.7 percent of the sales dollar. Operating costs are about 85 percent of this gross margin, leaving about 2.5 percent of the sales dollar as income before taxes. After taxes the profit is reduced to about 1.3 cents on the sales dollar.

Table 1. IMPACT OF "TILT" REGULATION ON THE PROFITABILITY OF ALREADY EXISTING PETROLEUM REFINING CAPACITY*

(Dollars per "Standard" Unit of Sales)

	1979 Market Without Tilt	1979 Market With Tilt	1979 Market Percentage With Tilt
Revenue	$1.000	1.040	100.0
Crude Oil Costs	.833	.833	80.0
Gross Margin	.167	.207	20.0
Operating Costs	.142	.142	13.6
Net Margin Before Taxes	.025	.065	6.4
Net Margin After Taxes	.013	.033	3.3

*For sources and assumptions, see text, pp. 16-19.

The effect of tilt can be assessed to a first approximation as follows: Let us assume that there is no change in the product output mix or in any of the refinery operations or facilities as a result of the availability of the tilt incentive, so that there is no change in crude oil costs or in operating costs. The only change would then be in the allowable revenue for the refinery's total output. If only gasoline is price controlled (ignoring for the moment the remaining price controls presently in effect for propane, butane, and natural gas liquids), then the result of tilt is to justify additional charges for gasoline based on ten percent of the increase in crude oil costs since 1973, for that fraction of the crude oil stream converted into gasoline, plus 25 percent (i.e., .70 - .45) of the increase in operating costs since 1973. A refinery with a capacity of 200,000 b/d producing 45 percent gasoline and 55 percent other products would have annual total sales revenues of about one billion dollars, with crude oil costs of about $833 million and operating costs of $142 million, leaving net income before taxes of about $25 million, and $13 million after taxes, or about 1.3 percent of the sales dollar, as shown in Table 1. This is the pre-tilt situation where it is optimistically assumed that market conditions permit recovery of all costs through aggregated sales in all markets summing up all products whether with or without price controls. As far as gasoline sales go, it is assumed that prior to tilt only 45 percent of the increased costs of crude oil could be charged against gasoline, and similarly only 45 percent of the increased cost of refinery operations. If we assume conservatively that $500 million of the $833 million crude oil purchase cost represents cost increases above the 1973 level, then gasoline cost pass-throughs increase from $225 million to $247.5 million, an increase of $22.5 million. If we also assume conservatively that $70 million of the $142 million annual operating cost represents cost increases since 1973, then cost pass throughs for gasoline from this source increase from $31.5 million to $49 million, an increase of $17.5 million. Thus total revenues would rise by $40 million per year, assuming that market conditions permit gasoline prices to be increased enough to secure the additional $40 million now obtainable under "tilted" price regulations. The effect of this $40 million increase in revenues, with fixed costs, is shown in the last two columns of Table 1. Income before taxes increases to $65 million and to $33 million after taxes. The gross margin increases from 16.7 percent to 20 percent of the sales dollar. Operating costs amount to only 13.6 percent of the larger total revenue, and the profit per gallon as a percent of the sales dollar for all refined products would rise from 2.5 percent to 6.4 percent before taxes and from 1.3 percent to 3.3 percent after taxes. Thus, the increasing of total revenues by 4 percent without increasing total costs raises the profit rate after taxes from 1.3 percent of the sales price to 3.3 percent, a significant improvement.

Hence, the inducement to operate existing facilities is definitely improved insofar as returns to an unchanged existing refinery are concerned. It is quite different, however, with respect to the returns to new investment in octane capacity. Table 2 shows how tilt would work in this context. The data of Table 2 are based upon unpublished studies by oil companies, and assume the existence of a typical 300,000 barrel per day refinery producing a 45 percent gasoline yield of which 50 percent is leaded and 50 percent unleaded. The contemplated investment is the installation of a 30,000 barrel per day light virgin naphtha isomerization unit which will cost $75 million to construct, and which has annual operating costs of $7.2 million for crude oil input, $9.0 million for other operating expenses, and which will be allowed straightline depreciation at $6.0 million per year. When this unit is in operation the gasoline output of the refinery will remain at 45 percent of total crude oil input, but will be 100 percent unleaded. There will be no change in the total crude oil input to the refinery.

Table 2 shows that although the fuel cost of the crude oil supplied to the new unit is $7.2 million per year, no cost recovery is permitted for this expense. This is one of the weaknesses of existing regulations. Unless net new crude oil input is required to permit the operation of a new facility, there is no allowance made for the fuel costs of such investments. At first glance it might seem that to allow for such fuel costs would involve double counting of crude oil costs since there is after all no actual increase in crude oil input in this case. It is important to realize, however, that under existing regulations the failure to allow the crude oil costs of such a specialized facility to be credited entirely to gasoline production costs means that the relevant crude oil costs are allocated to gasoline only to the extent of 45 percent rather than 100 percent, and that full recovery of the other 55 percent is problematical, especially since the decontrol of other refined

Table 2. IMPACT OF "TILT" REGULATION ON THE PROFITABILITY OF NEW INVESEMENT IN GASOLINE OCTANE ENHANCEMENT CAPACITY

	Annual Costs ($ Million)	1979 Market without Tilt		1979 Market With Tilt	
		$ Million/Year	¢/Gallon	$ Million/Year	¢/Gallon
Costs Recovered Under Regulation:					
Crude Oil	7.2				
Other Operating Costs	9.0	4.0	.19	6.3	.29
Depreciation[a]	6.0	2.7	.13	4.2	.21
Total Recovery	22.2	6.7	.32	10.5	.50
Price/Gallon Change		10.5	.50	10.5	.50
Allowable Revenue Increase		17.2	.82	21.0	1.00
Actual Operating Costs		22.2	1.07	22.2	1.07
Net Income Before Taxes		-5.0	-.25	-1.2	-.07

Source and Notes: See Text, pp. 13-19.

products prices and the elimination of the banked costs associated with them. The point is that in the evaluation of a new investment concerned solely with the production of gasoline from a specific part of the crude oil stream, the project must be evaluated at the margin in terms of the precise incremental costs and revenues associated with that particular investment. This necessity is all the more binding under existing regulations where the product in question--gasoline--is price controlled with the others not being controlled. (If other products were currently price-controlled on a cost-justification basis, then it would be appropriate to deduct from total crude oil costs the cost of the crude oil input to the isomerization unit when computing the cost of crude oil embodied in other products. Since such a distinction was not made during the period when other products were price regulated, and since these products are no longer price regulated, the only prudent approach is to compute the profitability of the new investment on its own terms, given the constraints imposed by existing regulations.)

Thus in terms of an economic profitability analysis, the crude oil costs of the input to the isomerization unit are lost. For other operating costs, recovery prior to tilt was 45 percent of such costs, such that only $4 million of the $9 million cost could be recovered against gasoline sales. Recovery of depreciation is limited to a straight-line basis, with 45 percent of the actual $6 million annual cost expiration being only $2.7 million. Thus total recovery of operating costs and depreciation before tilt was only $6.7 million out of an actual total of $22.2 million. The allowable revenue increase before tilt thus consisted of this $6.7 million plus the one cent per gallon greater margin obtainable from unleaded gasoline. Since the gasoline output is now 100 percent unleaded instead of 50 percent, the average price per gallon increases by half a cent, providing another $10.5 million per year, for a total annual revenue increase of $17.2 million. But since the increase in operating costs is $22.2 million, the net income before taxes is a loss of $5 million per year. On a per-gallon basis the loss is .25 cents.

Tilt improves the situation but still leaves a loss. The recovery factor on other operating costs and depreciation increases from 45 percent to 70 percent, cutting the losses on operating costs to $1.2 million per year, and reducing the loss per gallon to .07 cent. But the rate of return is still negative, acting emphatically to discourage investment. The data underlying Table 2 can also be used to compute the price differential between leaded and unleaded gasoline which would be necessary to yield a competitive 12 percent discounted cash flow rate of return on the necessary investment. To recover the $22.2 million additional annual operating cost and obtain the necessary net income before taxes ($15.3 million per year), an annual revenue increase of $37.5 million would be necessary, which could be provided by an increase of 3.5 cents per gallon in the existing differential between leaded and unleaded gasoline. Assuming that an unregulated competitive market would require a 12 percent dcf rate of return on investment, such a computation suggests that the decontrol of gasoline prices might require such an additional price differential to supply growing unleaded gasoline demands. By way of contrast, in order to obtain the same 12 percent dcf rate of return under the tilt regulations, the allowable profit margin for unleaded gasoline would have to be increased by 1.6 cents per gallon. This increase does not compare directly with the 3.5 cent differential under decontrol since under regulation the 70 percent pass-through of non-operating costs and depreciation helps the economics of the new investment.

Before leaving this topic, it might be mentioned that estimates were obtained from oil refining economists for two major companies regarding the cost of converting a typical 200,000 barrel per day refinery producing 100,000 b/d of gasoline from a 45 percent unleaded yield in 1979 to an 80 percent unleaded yield in 1985. Both estimates were in the $50 to $60 million range. If we assume that the refining industry, with an input capacity of about 16 million barrels per day, consists of 80 such refineries, then a first-approximation scale up would indicate costs of from $4.0 to $4.8 billion dollars for this conversion. This cost is higher than the $2-$3 billion dollar range recently estimated by Mr. C. R. Sitter of Exxon in a May 1979 statement before an EPA hearings committee.

3. THE "MARKET SHARE PROTECTION" RATIONALE FOR OCTANE ENHANCEMENT INVESTMENT

"Tilt", therefore, appears not to be the answer to the unleaded gasoline shortage for several reasons: fuel costs are not recovered, non-operating costs are only about 70 percent recovered, and the existing per barrel or gallon profit margin is not adequate in the light of current investment costs. Nevertheless, oil companies continue to make some investments in increasing unleaded gasoline production capacity. Why is this?

As indicated in the introduction, if an oil company intends to stay in the gasoline business, it will cost more not to make these investments than to make them, even at some loss. Not making these investments means sacrificing market share to those who do make them. The largest companies have the greatest stake in the continuing viability of the U.S. energy sector, and indeed of the U.S. economy generally. Smaller companies can diversify out of refining by failing to invest in unleaded capacity, but this is tantamount to surrendering the unleaded market to other firms. Executives of several major firms interviewed by the author gave the same views. They explained that some degree of optimism regarding the eventual lifting of price controls was always necessary to justify decisions to invest in octane capacity, but the decisions have been getting harder and harder to justify over time given the failure of gasoline price controls to be lifted. The companies realize that they have to move ahead in unleaded capacity to keep up with market demand, but in practice the decision to go ahead with a new major project takes longer and longer to reach and implement. Delay becomes second nature since putting off the project another few weeks or months may allow some time for possible decontrol to occur. Thus companies try to minimize the direct new investment involved in octane capacity expansion, choosing "debottlenecking" adjustments over the construction of new capacity wherever possible, even though they realize this is a short term strategy which, while it saves on capital costs, will increase operating costs and input purchases. But since these latter cost categories can be recovered at least in part under existing regulations, while the rate of return on new investment is presently negative, debottlenecking may be preferable. Also, instead of building new processing units, the firm may deem it preferable to use different catalysts in existing units, improving operating yields but at the expense of higher operation costs--which can still be at least partly recovered under regulation. Or the refinery output mix may be altered by moving away from petrochemical feedstocks into aromatics, easing octane capability pressures but creating supply shortage problems elsewhere.

The effect of price and lead content regulations has naturally varied from company to company. Some companies such as Amoco had unleaded capacity in 1973. Some companies possessed refinery facilities which made it somewhat easier to meet EPA lead content phasedown requirements pertaining to the entire gasoline pool of the company; others had to invest more heavily in octane capacity at an earlier stage, in order to meet EPA mandates. But since, under price regulation, there was little chance for any company to recover its investment in new facilities on any kind of project, everyone tended to do no more than was absolutely necessary in their particular situation. Only the best projects were accepted; borderline proposals were rejected.

Another aspect of the market share issue is the fact that no company was certain of the plans of others. One company might plan to invest in unleaded capacity in order to maintain its market share, but if other companies did not do the same, then the new capacity developed by the investors would be sought out by customers and there would seem to be a shortage of capacity on the part of the companies that had done the most to meet it.

A further factor confusing the unleaded market was the automakers' tactic of designing higher compression engines to meet automobile fuel economy standards. An alleged informal agreement between the automakers and the Ford administration was reputed to obligate Detroit to keep engine compression standards down to the point where regular grade unleaded gasoline would be adequate to insure engine performance satisfactory to car owners. But somehow compression standards increased and with it, the demand for higher octane fuel. It is variously estimated that from 25 to 50 percent of the newest cars cannot use regular grade unleaded gasoline without performance impairment. One assessment is that 25 percent of late model cars cannot run well on available unleaded gasoline with an 87 octane rating. 17 percent still can't run acceptably on higher grade 88.5 leadfree gasoline, while only about 4 percent require more than the 92/93 octane unleaded premium gasoline recently introduced by Mobil. Mobil's new product qualified for a 4 to 5 cent per gallon price premium above unleaded regular, since its price is related to that of leaded premium gasoline sold in 1973.

Much unleaded gasoline capacity was obtained simply by phasing leaded premium gasoline out, as older cars were retired from the motor vehicle population. Leaded premium accounted for roughly 30 percent of gasoline sales in 1973, but was down to 14 percent in 1978 and is estimated at 12 percent for 1979.

The market share argument remains valid only as long as the market for which sellers are competing is expected to be profitable in the long run. But given this assumption (which the most pessimistic refiners may not currently share) there is a well established school of thought in economics and marketing which holds that maintenance of the firm's market share is a crucial determinant of a producer's price and production policies. This idea had been current in marketing circles for many years, but was not introduced into the mainstream of the microeconomic analysis of the individual firm until Baumol's formulation of the sales maximization hypothesis in his book, *Business Behavior, Value, and Growth* in 1959. (A decade and more earlier, however, Joel Dean had dealt with some of these issues, in applied contexts, in his *Managerial Economics.)* Baumol pointed out that the usual economic assumption that business firms used profit maximization as the only criterion of price and output decisions overlooked the fact that the decision makers, usually not being major stockholders themselves, might identify their careerist interests with the size of the firm rather than its profitability and attempt to maximize sales volumes, subject only to the constraint of earning a rate of return which would be at least satisfactory to stockholders. Maximizing size means maximizing market share, and companies which follow this strategy are likely to be anxious to increase their market penetration and very reluctant to have it reduced by the actions of other firms.

4. AN ASSESSMENT OF THE FACTORS RESPONSIBLE FOR THE CURRENT SHORTAGE OF UNLEADED GASOLINE

It therefore appears that the cause of the current shortage of unleaded gasoline is not to be traced to any decision by producers that they should persist in the production of leaded gasoline only, since the profits are greater there, and thus force buyers to switch from unleaded to leaded gasoline as the inevitable shortages arise. Instead, the causes of the current shortages of unleaded gasoline are primarily due to the failure of Iranian oil production to reach its pre-revolution level, coupled with the decision of other OPEC members not to increase their outputs to make up the difference. The shortage is therefore a crude oil shortage, not so much a shortage of unleaded gasoline as of gasoline generally, and to a lesser extent a latent shortage of all refined petroleum products. Before the Iranian revolution there was to some extent a relative shortage of octane capacity for producing unleaded gasoline, but with adequate oil imports this problem was regarded as manageable. After the Iranian cutbacks the problem became one of a quantity shortage rather than a quality shortage, with all products being at least potentially in short supply since crude oil imports had fallen.

As mentioned in the introduction, the temporary disappearance of Iranian oil exports during the first quarter of 1979 was not immediately felt since inventories were drawn down to minimize consumer inconvenience, and there was a time lag of over a month in oil deliveries from Iran. During the Iranian shutdown Iranian exports dropped by about 5 million barrels per day, but more than half of this amount was made up by increased exports from other

Persian Gulf producers (notably Saudi Arabia) and from Venezuela and Nigeria. After the restoration of Iranian exports was under way, however, other OPEC members cut back their output levels, notably Saudi Arabia, whose cutbacks were more precipitous than had been expected. This haste in reducing output was interpreted in many quarters as retaliation for the U.S. role in the Egyptian-Israeli peace settlement. Other Arab producers were also less than enthusiastic about maintaining their increased output levels, not only due to hostility toward the peace settlement, but also to keep oil output scarce and oil prices rising. OPEC members were all but unanimous in opportunistically increasing oil prices through special surcharges and other levies during and after the Iranian revolution. The shortfall of world crude oil production was about 2 million barrels per day during the first quarter of 1979, but at present Iranian output is still about 2 million barrels per day below historical levels, with the world crude oil supply shortfall still almost as great as it was during the Iranian revolution.

During the first quarter of 1979 the U.S. crude oil supply shortfall was about 900,000 barrels per day, some 5 percent of total refined products consumption. But delivery lags and inventory reductions offset the impact of the crude oil shortage so much that actual U.S. petroleum products consumption increased by about 1 percent in the first quarter of 1979 relative to 1978. Inventories of all refined petroleum products had been reduced to minimal levels during the first quarter of 1979, and have to be restored. This is particularly true of heating oil stocks, which must be built up to adequate levels in time for the beginning of the winter heating season. But doing so during the summer will squeeze back gasoline production during the seasonal peak of gasoline demand. April 1 inventories of gasoline and distillates were about 35 million barrels below average levels and were close to the minimum feasible volumes for working inventory purposes. It appears likely that total refinery runs in the U.S. will be no greater in the summer of 1979 than in 1978, while demand is predicted to increase by at least one percent. Restoring inventories to desirable levels will require that 2 or 3 percent of summer production be placed in storage rather than put on the market. Thus with the one percent demand growth anticipated, a shortage of from 3 to 4 percent in refined petroleum products availability is likely to persist throughout the summer, and probably for an indefinite period.

But if the crude oil shortage is about 4 percent it is unlikely that this shortage will be spread evenly over all products. It is more likely, for example, that gasoline shortages will be perhaps 6 percent while distillate shortages might be more like 2 percent. The Carter administration has been urging the oil industry to produce more distillates and less gasoline just now, in order to build up heating oil inventories, a position which the industry itself is in favor of. In May 1979, however, Carter at least temporarily reversed his position, asking refiners to increase the share of gasoline in the output mix. It is still too early to appraise the extent of the industry's response to this suggestion.

Current oil import levels are below those of a year ago by more than half a million barrels per day. In order to meet higher consumer demands and inventory replenishment needs, imports should in fact be well above last year's levels. In addition, since domestic production has been declining since 1970, higher imports are also needed to compensate for this steady reduction in domestic output. But with OPEC unwilling to increase total output by enough to make up for the Iranian shrinkage, those OPEC members who are inclined to sell extra oil from time to time on the spot market are doing so in order to obtain high prices rather than to augment world supplies. The U.S. government has informally warned domestic companies not to bid excessively high prices for spot market offerings of OPEC oil, suggesting that prices of more than $20 per barrel may not be allowable for cost pass-through purposes. Here, too, it would seem that many U.S. companies are in principle in agreement with DOE urgings, concurring that such sales will do more to raise OPEC revenues and future price demands than to raise world oil supplies. Still, the reluctance of U.S. companies to bid high prices has meant that European and Japanese buyers have been obtaining the major share of OPEC spot oil supplies, and lately the U.S. government has reversed its position, giving companies permission to make high bids without fear of losing cost pass-throughs. Again, it is too early to gauge industry response to this reversal of the government's stance.

A very rough estimate of the quantitative importance of the above factors in contributing to the current U.S. crude supply shortfall would be as follows: Iranian output reduction, 80 percent; decline in U.S. domestic production, 10 percent; reluctance of U.S. companies to participate vigorously in spot market bidding, 5 percent; other factors, 5 percent.

5. POLICY OPTIONS FOR DEALING WITH THE PROBLEM OF MISFUELING

The best way to increase supplies of both leaded and unleaded gasoline is to find ways of getting more crude oil. Domestic crude oil price decontrol would be the best solution but it is long run in nature. In the short run, if OPEC will not sell more oil, then importing nations must simply do without. Again, the appropriate response is a price response. Conservation must be achieved, and higher prices provide the best long run incentive to practice conservation. Hence the most efficient proposal would be to decontrol gasoline prices and allow them to rise, increasing domestic production, decreasing consumption rates, and bringing supply and demand into balance.

But if OPEC will not increase oil exports, for reasons best known to itself, it is also to be feared that Washington will not decontrol gasoline prices, for similarly inscrutable reasons. The economist is then asked to compare alternative policies all of which are inferior to market price measures. Should leaded/unleaded gasoline price differentials be arbitrarily limited by various means?

If unleaded gasoline is in fact in short supply relative to leaded gasoline, then the situation could be remedied at least to some extent if the price differential in favor of unleaded gasoline could be further increased. The example given in Section II of this paper indicated that an increase in the unleaded gasoline profit margin of about 1.6 cents per gallon would permit competitive earnings on investments in new octane capacity. The EPA, on the other hand, wants to reduce the price differential between leaded and unleaded gasoline by cutting the price of unleaded gasoline. To an economist such a proposal seems most misguided.

The EPA argues that motorists switch from unleaded to leaded gasoline in order to save a couple of cents per gallon; hence making unleaded gasoline cheaper would eliminate this incentive. It seems much more likely, however, that voluntary switching occurs for performance rather than price reasons. If a car won't run well on unleaded gasoline, switching to leaded gasoline seems like a good idea to the motorist, even though in the long run it will mean more air pollution. If the benefits of reduction of this sort of air pollution are in fact worth the costs of control, the economist would advise two measures: (1) increase the quality of unleaded gasoline, which requires increasing its price; and (2) possibly place an air pollution tax on leaded gasoline, raising its price relative to that of unleaded gasoline. How large a pollution tax, if any, on leaded gasoline is justified on air pollution and anti-switching grounds is a matter for empirical cost-benefit analysis, but while the raising of the prices of both leaded and unleaded gasoline would have a beneficial conservation effect in reducing gasoline consumption, a differentially higher price for leaded gasoline would be likely to reduce fuel switching only if the quality of unleaded gasoline were to be improved at the same time. On the other hand, lowering the price of unleaded gasoline will either reduce its quality or its availability, inducing still more fuel switching.

MISFUELING ESTIMATES AND AIR QUALITY EFFECTS

Pythagoras Cutchis and Robert C. Oliver

1.0 INTRODUCTION

As discussed elsewhere in this report, at least three factors lead to misfueling: these include performance factors (knock, dieseling), cost differential effects, and shortages. The quantitative aspects of these factors, and how they interact, will be at issue for some time (Ref. 1-4, as examples). Some estimates at the present time however, using available models, and modifications thereof, may be useful for policy purposes in spite of their tentative nature, and are provided in the following materials.

Two misfueling models (or estimating procedures) have been provided us by EPA. The first of these (Ref. 1), which we refer to as the Nussbaum and Neal model, is concerned with misfueling due to the price differential between leaded and unleaded gasoline. The second, or Nevitt's model (Ref. 2) is concerned with the issue of misfueling due to shortages of unleaded gasoline. No model is available specifically relating misfueling to octane inadequacies of unleaded fuel, but the Nussbaum and Neal model, based on the underlying Sobotka (Ref. 3) report and other data, shows misfueling estimates at 0¢ price differential, which may be interpreted as octane-pool switching.

As considerable discussions will be devoted to these two models, the assumptions implicit in their development must be recognized. The principal assumption for the Nussbaum and Neal (Ref. 1) and Sobotka (Ref. 3) surveys are as follows:

1. At the time of the Sobotka survey gasoline of all types was in adequate supply: the model assumes this situation to pertain.

2. The average price of gasoline was in the 60¢/gallon range, so that a 6¢/gallon differential, e.g., was undoubtedly perceived as being of more significance than would be the same differential with gasoline at say $1.00 per gallon.

3. The Sobotka questionnaire made no reference to possible penalties, illegalities, adverse environmental impact, etc. of misfueling. This may have led to high estimates of the misfueling potential.

4. The response-time question was not addressed in the model; i.e., older cars were found to have higher misfueling rates for given price differentials than newer cars, but the question of how long a given price differential would be "endured" before a driver would take action is unknown. We have assumed this time to be relatively short ($\lesssim$ 3 months).

5. No "feedback" effects were included, in line with the basic assumption of unlimited supplies of both types of fuel. Large switching rates would in fact effect price differentials and shortages.

The Nevitt model (Ref. 2) is directed towards predicting misfueling due to shortages of unleaded gasoline; it assumes adequate supplies of leaded gasoline. The model is purely statistical; i.e., with a specified, say 10 percent, shortfall of unleaded gasoline, it assumes that a motorist has one chance in ten of being forced to buy leaded gasoline. (How he does this, without prior preparation, is not discussed). After this happens three times (for which the calendar time required depends on the number of tanksful he uses in a given period) the catalyst is assumed to be destroyed. Perhaps the most impressive aspect of this model is the time-dependence; shortages at any level eventually lead to destruction of all catalysts. We here use this same modeling approach to indicate catalyst destruction, assuming a single tankful of leaded gasoline, as well as three, will cause catalyst destruction, as the information accompanying this second modeling paper (Ref. 2) suggests this may be the case with 3-way catalysts which are to be used on a large percentage of 1980 cars.

Fragmentary data on regeneration of catalysts following use of leaded gasoline exists. The data are discussed, and effects noted, following consideration of these two models.

An obviously important point from a policy standpoint, which is not treated in this section, is the possible interaction of price differential and shortages on misfueling: if an imposed low price differential leads to shortages, the reduction in misfueling by one cause may be more than counter-balanced by misfueling due to the other cause. However, other aspects which we believe to be of policy interest, relate to the effects of (1) a temporary increase in price differential, followed by a mandated return to a lower level, and (2) a temporary shortage of unleaded gasoline. These are explored in some detail. Finally, air quality effects are considered briefly.

2.0 MISFUELING ESTIMATES AND EMISSION FACTORS

2.1 PRICE DIFFERENTIAL EFFECTS (ADEQUATE SUPPLIES)

2.1.1 Introduction

Emission factors for light duty vehicles have been calculated by EPA (Refs 1 and 5) for the years 1981-1985 based on the Sobotka study of fuel switching rates and EPA observations. The model indicates misfueling increases sharply with the price differential between leaded and unleaded gasoline and with age of vehicle. Here we use those results, and extend the methodology to estimate the impact of a hypothetical rise in 1979 from an assumed current 4¢* price differential to an 8¢ price differential, followed by a hypothetical regulation imposing either a return to the current 4¢ or a 0¢ price differential. It is assumed that this regulation subsequently remains in effect for the period 1980-1984. We assume switching to be maintained once it starts, so that any regeneration is of no significance.

2.1.2 EPA Misfueling Estimates

The fuel switching rates used by EPA (Ref. 1) are reproduced in Table 1. Note that a 4 year old light duty vehicle (LDV) with a catalytic converter is associated with a fuel switching rate about 50 percent greater than for a new vehicle, and that the fuel switching rate for an 8¢ price differential is almost an order of magnitude higher than for a 0¢ price differential independent of vehicle age. The fuel switching rates for catalyst-equipped vehicles older than four years (or five now) are projections, as no such vehicles are now in the fleet.

Table 1. FUEL SWITCHING RATES BY PRICE DIFFERENTIAL (REF.1)
(In Percent)

Age	Differential				
	0	2	4	6	8
1	3.60	6.60	9.00	18.69	33.69
2	3.56	6.53	8.90	18.39	33.23
3	4.16	7.63	10.40	21.49	38.83
4	5.40	9.90	13.50	27.90	50.40
5	5.63	10.41	14.20	29.35	53.01
6	6.28	11.51	15.70	32.45	58.61
7	6.88	12.61	17.20	35.55	64.21
8	7.48	13.71	18.70	38.65	69.81
9 or more	8.08	14.81	20.20	41.75	75.41
Composite Rate	5.56	10.20	13.91	29.75	51.94

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*If the current price differential is 5¢, the effects can be readily interpolated.

2.1.3 Hydrocarbon Emissions

In Figure 1 the hydrocarbon emissions in grams/mile are plotted for various price differential histories over the period 1979-1984 using the EPA model (Ref. 1). Calculated values for the 1979 and 1980 calendar years were added by IDA to available calculations made by EPA for the years 1981-1984 for constant price differential (solid lines in Figure 1). Also plotted for reference purposes is the case for no fuel switching which, as indicated earlier, is not realistic, as some drivers switch for purely performance reasons. The following conclusions can be drawn from these constant price differential curves:

1. The HC composite emission factor for a constant 4¢ price differential in 1979 is only 4.6 percent higher than a constant 0¢ price differential, but increases linearly to 17.5 percent higher by 1984.
2. The HC composite emission factor for a constant 8¢ price differential in 1979 is 19 percent higher than for a constant 4¢ price differential, and increases linearly to 68 percent higher by 1984.
3. The rate of decrease with time of the composite emission factor decreases with increasing price differential. For the constant 8¢ price differential there is only a 6.5 percent decrease in the HC composite emission factor between 1979 and 1984.

At the bottom of Figure 1 is shown a hypothetical price differential history in which the current 4¢ price differential increases to 8¢ due to market forces during the middle of 1979, followed by a period of several months at a constant 8¢. A hypothetical regulation is assumed to be implemented by the time the 1980 vehicles are on the market which reduces the price differential to either 0¢ (Case A) or 4¢ (Case B) until 1984.

The dashed lines in Figure 1 represent the calculated HC composite emission factors for Cases A and B. In these calculations it was assumed that during the several months for which the price differential was 8¢ in 1979 the owners of vehicles with catalysts switched from unleaded to leaded fuel in accordance with the 8¢ fuel switching rates of Table 1. It was

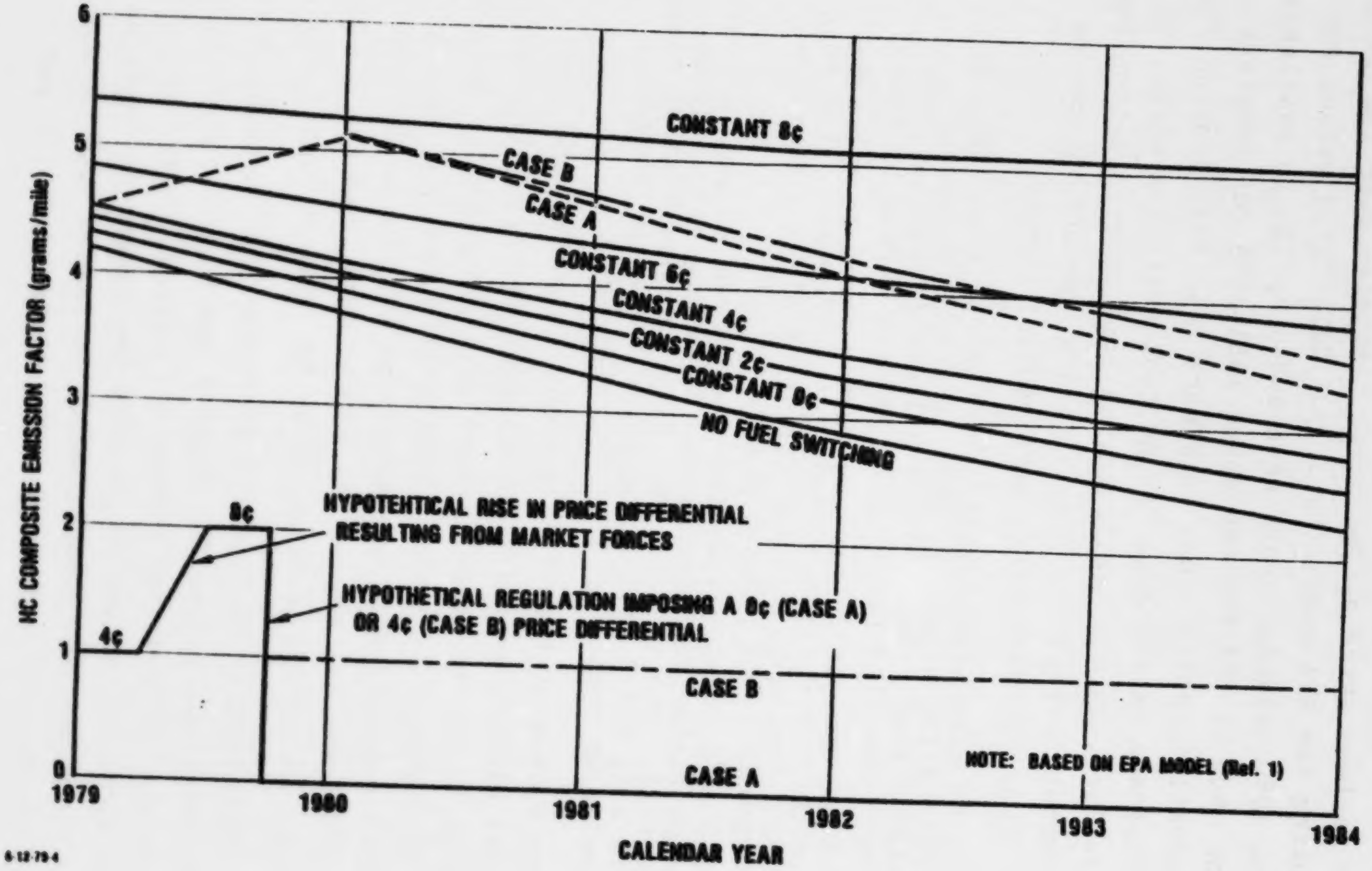

Figure 1. HC COMPOSITE EMISSION FACTOR FOR HYPOTHETICAL PRICE DIFFERENTIAL HISTORIES IN THE PERIOD 1979-1984

further assumed that the number of poisoned catalysts resulting from this fuel switch (for a given model) remained constant after the imposition of the price differential regulation. Thus, in 1980 the owners of 1980 vehicles were assumed to switch at a rate corresponding to a 0¢ price differential (Case A) or a 4¢ price differential (Case B); in 1981 the owners of 1981 as well as 1980 vehicles were assumed to be switching at the 0¢ or 4¢ price differential rates, etc. The HC composite emission factor would with these assumptions be reduced with each subsequent year as more new model cars joined the LDV fleet with their unpoisioned catalysts. Conclusions that can be drawn from Figure 1, assuming the model on which it is based applies, are:

1. If the current price differential is allowed to increase from 4¢ to 8¢ and vehicle owners switch fuel at the 8¢ price differential rates, recovery of the HC composite emission factor will be slow. Not until after 1985 will the HC factor equal the value that it would have been if there had been no increase in price differential in 1979.
2. A price differential regulation of 0¢ (Case A) is only slightly more effective in reducing the HC composite emission factor than one of 4¢ (Case B); e.g., it will result in an emission factor which intersects the constant 6¢ price differential curve six months earlier during calendar year 1982.
3. If the price differential history 4¢-8¢-4¢ (or 0¢) occurs in 1980 rather than in 1979, emissions will be higher because a larger fraction of the LDV fleet will have polluted catalysts.

2.1.4 Effects on Carbon Monoxide Emissions

In Figure 2 the CO composite emission factor is plotted against time for the same price differential histories that were calculated for HC (Figure 1). A comparison of Figure 2 and Figure 1 shows that:

1. The CO composite emission factors are more than an order of magnitude higher than the HC composite emission factors for all price differentials and all years.

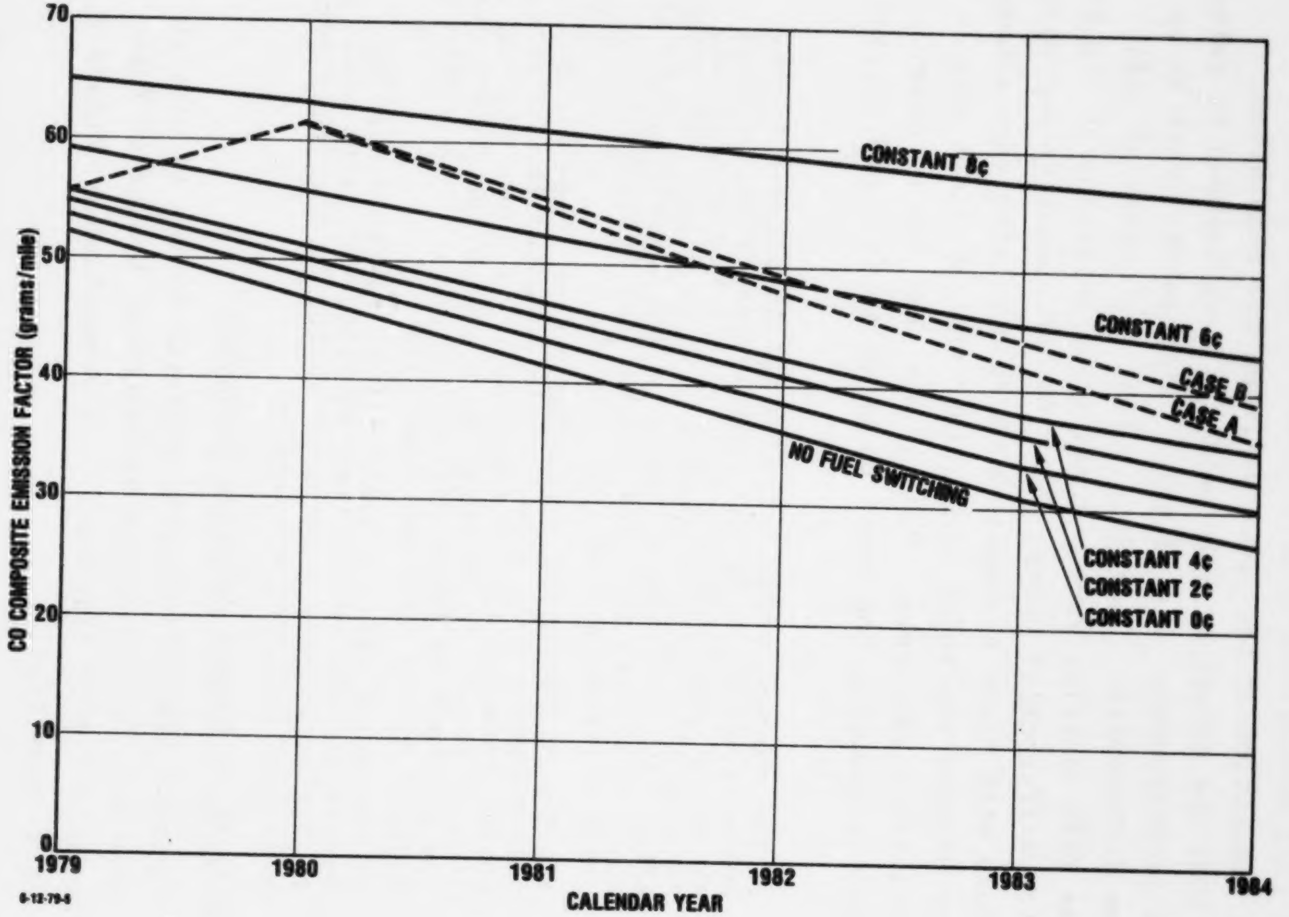

Figure 2. CO COMPOSITE EMISSION FACTOR FOR HYPOTHETICAL PRICE DIFFERENTIAL HISTORIES IN THE PERIOD 1979-1984

2. For a constant price differential, the rate of reduction in the composite emission factor for CO is slightly higher than for HC, i.e., the slopes of the solid lines are somewhat greater for CO.

3. For Cases A and B, the recovery rates are somewhat higher for CO than for HC, e.g., the 6¢ constant price differential curve is intersected some six months earlier than was the case for HC.

In the calculations made above, it was implicitly and (currently) incorrectly assumed that there are no fuel shortages and supply is in equilibrium with demand. Clearly any increase in fuel switching rates brought on by fuel shortages will exacerbate the effects due to an increased price differential.

2.2 UNLEADED GASOLINE SHORTAGE EFFECTS

2.2.1 Misfueling Due to Shortages

A shortage of unleaded gasoline may lead to an increase in the misfueling rate with an impact on emissions that will depend on the duration of the shortage and the number of misfuelings required to poison a catalytic converter. The expected fraction "f" of LDVs with poisoned catalysts can be calculated (under certain simplifying assumptions) as a function of the percent shortfall of unleaded gasoline X, the number of fuelings "n" per vehicle during the shortage, and the number of misfuelings "m" required to poison the catalyst (J.S. Nevitt, Ref. 2). If, (1) the percent shortfall is interpreted as the probability that a motorist will pull up to a gasoline station and find no unleaded gasoline for sale (implies a random distribution of shortages), (2) there are no shortages of leaded gas, (3) there is no recovery* on the performance of catalytic converter following misfueling, and (4) the motorist misfuels at such a station, then the expected fraction of LDVs with poisoned catalysts is given by the cumulative binomial probability distribution, or

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*Recovery is discussed in Section 2.3.

$$f = \sum_{i=m}^{i=n} \binom{n}{i} X^{i} (1 - X)^{n-i} . \qquad (1)$$

The fourth assumption above can be criticized on the grounds that the motorist encountering such a situation would continue to the next gasoline station in his search for unleaded gasoline. However, if he is successful, he is thereby decreasing the probability that some other motorist can successfully find unleaded gasoline. Over the entire fleet of LDVs with catalytic converters, X percent of the fuelings in a given week will of necessity be misfuelings, under the above assumptions. However, it is not unreasonable to expect that unnecessary trips would be minimized under a shortage, and the value of X would therefore be decreased to a smaller value than it otherwise would have been, i.e., conservation of fuel would tend to diminish the magnitude of the shortage, and X itself would be time-dependent. The value of X in Equation (1) is here assumed to be constant, and represents the percent shortfall of unleaded gasoline with respect to the driving habits of the motorists during the time of the shortfall, and not the the driving habits in the absence of a shortfall. Further complicating this interaction is the motorist's perception of a shortfall situation which is aggravated by long lines, topping off of tanks, early closings, etc.

The expected fraction of LDVs with poisoned catalysts, in accordance with Equation (1) and its underlying assumptions, is plotted in Figures 3 and 4 as a function of the number of fuelings during the shortage.* Values of X were assumed to range between 1 and 10 percent, and the number of misfuelings n required to poison a catalytic converter was assumed to be 3 (Figure 3) or 1 (Figure 4). The number of fuelings is related

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*Tables of the Cumulative Binomial Probability Distribution, Harvard University Press, 1955.

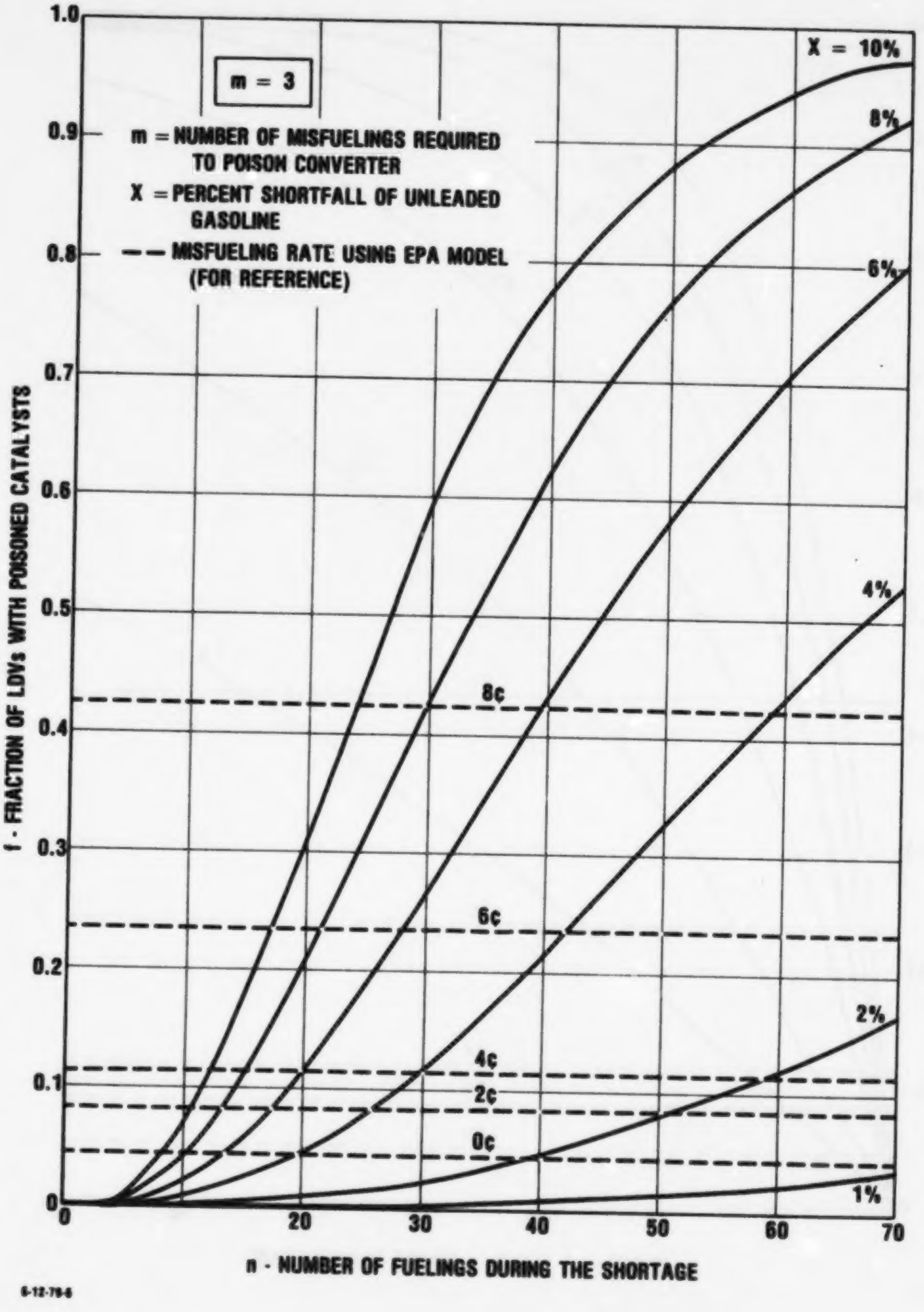

Figure 3. EFFECT OF UNLEADED GASOLINE SHORTAGE ON POISONING OF CATALYTIC CONVERTERS

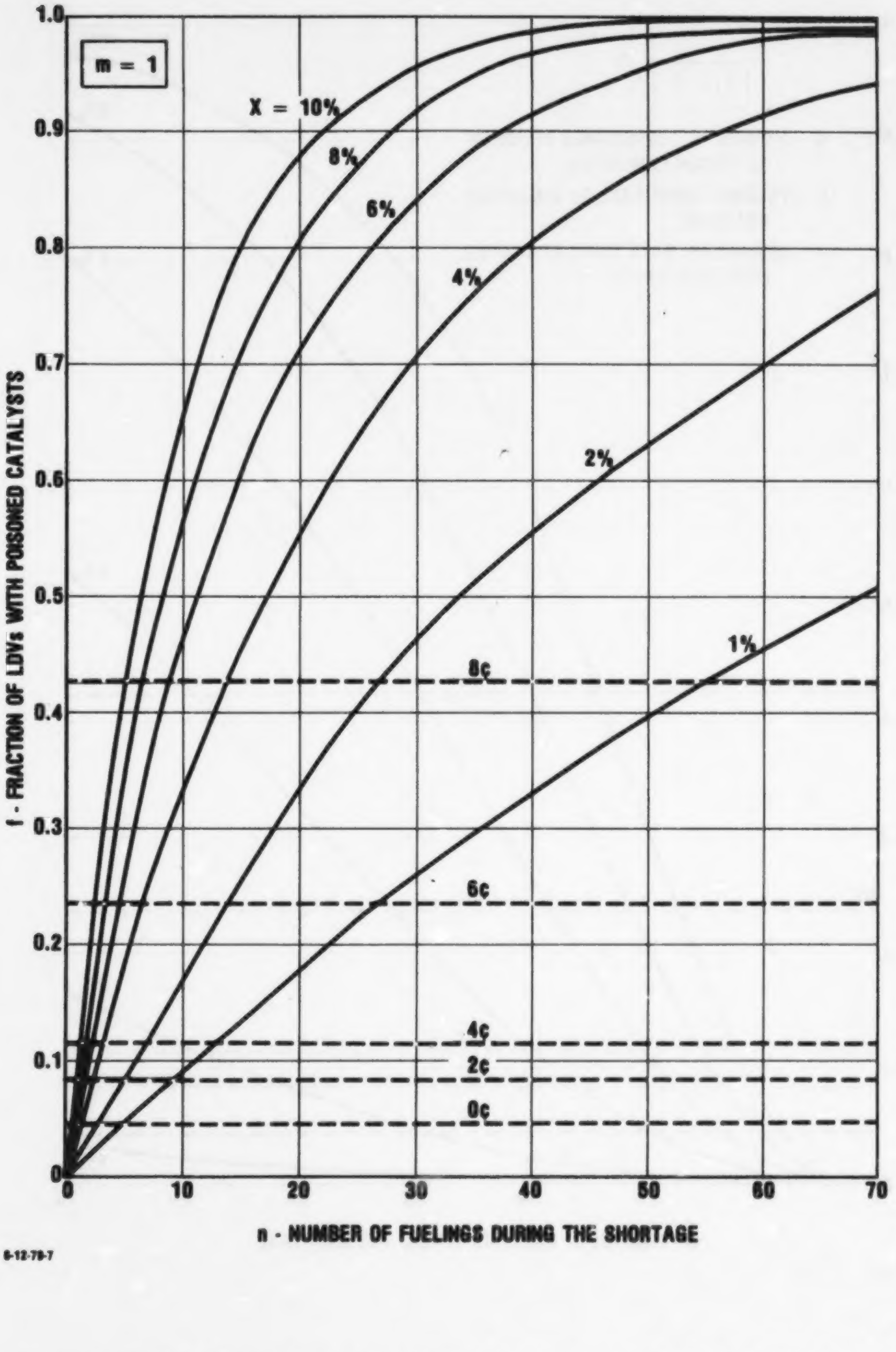

Figure 4. EFFECT OF UNLEADED GASOLINE SHORTAGE ON POISONING OF CATALYTIC CONVERTERS

to calendar time by frequency of fueling; one fueling per week might reasonably be assumed. The curves of Equation (1) were drawn with the aid of tabulated values of the cumulative binomial distribution. Figures 3 and 4 also show, for reference, misfueling rates at various price differentials, as calculated using the EPA model.

From Figure 3 it is seen that for m = 3 and a small fuel shortage X of one percent, the fraction f of LDVs with poisoned catalysts exceeds 0.01 only if the number of fuelings exceeds 40; for m = 1 (Figure 4) the comparable value of f is 0.33. A catalytic converter that is poisoned by a single misfueling therefore poses a far greater emission threat for a small shortage of given magnitude than one which requires three misfuelings.

As noted above, the horizontal lines in Figures 3 and 4 represent the misfueling rates by the EPA model for the labeled price differentials; these rates were obtained (for 1979) by weighting the rates of the 1975-1979 LDV fleet (Table 1) according to mileage by vehicle age (Ref. 5) ignoring any response-time effects. Note that if X = 6 percent and m = 3, 40 fuelings would produce the same 42 percent poisoning of catalytic converters as an 8¢ price differential (in 1979) with no unleaded gas shortage (Figure 3). If m = 1 instead of 3, the same shortage of 6 percent would require only 9 fuelings to have the same effect as an 8¢ price differential, and only 5 fuelings if X = 10 percent.

The principal conclusion of the above discussion is that a significant increase in HC and CO emissions could follow a prolonged shortage of unleaded gas. Indeed, the effects of such a shortage, by these models, could well exceed the effects of even a large price differential with no shortage.

Perhaps the greatest uncertainty in this modeling approach is the assumption that 3 misfuelings, at any spacing, will lead to catalyst destruction. Hard data on this subject do not seem to exist. However anecdotal data, as reported by the Los Angeles Times* suggest that a larger value of m may be appropriate for conventional (not 3-way) catalysts. Thus, according to the Los Angeles Times, citing Dr. Fred Bowditch of the Environmental Activities staff of General Motors, "With four or five tankfuls, the catalyst material can be regenerated, but if you use eight or ten tankfuls of leaded gas, one after the other, the catalyst probably is not able to regenerate." The same article cites also Charles Gray, Director of Motor Vehicle Emission Control at the EPA labs in Ann Arbor, Michingan, to the effect that "most evidence shows some damage after a single tankful of leaded gasoline, but an 80 percent to 90 percent recovery once use of unleaded fuel is resumed. After two tankfuls, recovery is only 50 percent to 60 percent and after four tankfuls only a 10 percent recovery is possible by switching back to unleaded fuel."

It is obvious, if a catalyst can regenerate after misfueling, that larger values of m should be considered in the misfueling calculations.** Some figures are given in Table 2. According to the binomial distribution model, for X = 10 percent and n = 30, over 95 percent of the catalysts would be poisoned if m = 1, whereas only 0.8 percent would be poisoned if m = 8. However, if n is increased from 30 to 100, the value of f for m = 8 increases from 0.8 percent to 79.4 percent.

2.2.2 Effects of Destroyed Catalysts on Emissions†

The effects on emissions due to catalysts destroyed during an unleaded gasoline shortage are indicated in Figures 5 and 6

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*Los Angeles Times, March 12, 1979. The data on which this article was based have been requested but not yet received. (June 5, 1979).

**The effect will vary with the sequence; this point is discussed in more detail in Section 2.3.

†Note that this treatment is in terms of destroyed catalysts, so that regeneration does not enter into this discussion.

Table 2. FRACTION OF CATALYSTS AFFECTED (f) WITH BINOMIAL DISTRIBUTION MODEL

X (Percent)	m	n = 10	n = 30	n = 100
1	1	.0956	.2603	.6340
	3	.0001	.0033	.0794
	8	.0000	.0000	.0000
5	1	.4013	.7854	.9941
	3	.0115	.1878	.8817
	8	.0000	.0001	.1280
10	1	.6513	.9576	1.0000
	3	.0702	.5887	.9981
	8	.0000	.0078	.7940

for HC and CO respectively for the LDV fleets of 1979 and 1980. Catalysts here were assumed to be destroyed at a misfueling rate (abscissa in Figures 5 and 6) which is independent of vehicle age, and the composite emission factors were calculated for the entire fleet using the EPA tables in Ref. 5. Under this assumption, the HC and CO composite emission factors are linear functions of the percent catalysts destroyed. For a small percentage of catalysts destroyed, each composite emission factor would be higher for 1979 than for 1980; for nearly 100 percent catalysts destroyed, each composite emission factor would be higher for 1980.

The percent increase in emissions for a 100 percent destruction of catalysts is given in Table 3; percent increase in emission for an α percent destruction of catalysts is readily obtained from the values in Table 4 by multiplying by α.

2.3 A MODEL OF CATALYST EFFICIENCY RECOVERY FOLLOWING MISFUELING(S)

The data quoted in the Los Angeles Times article (Section 2.2) can be used to develop a model for catalyst deactivation

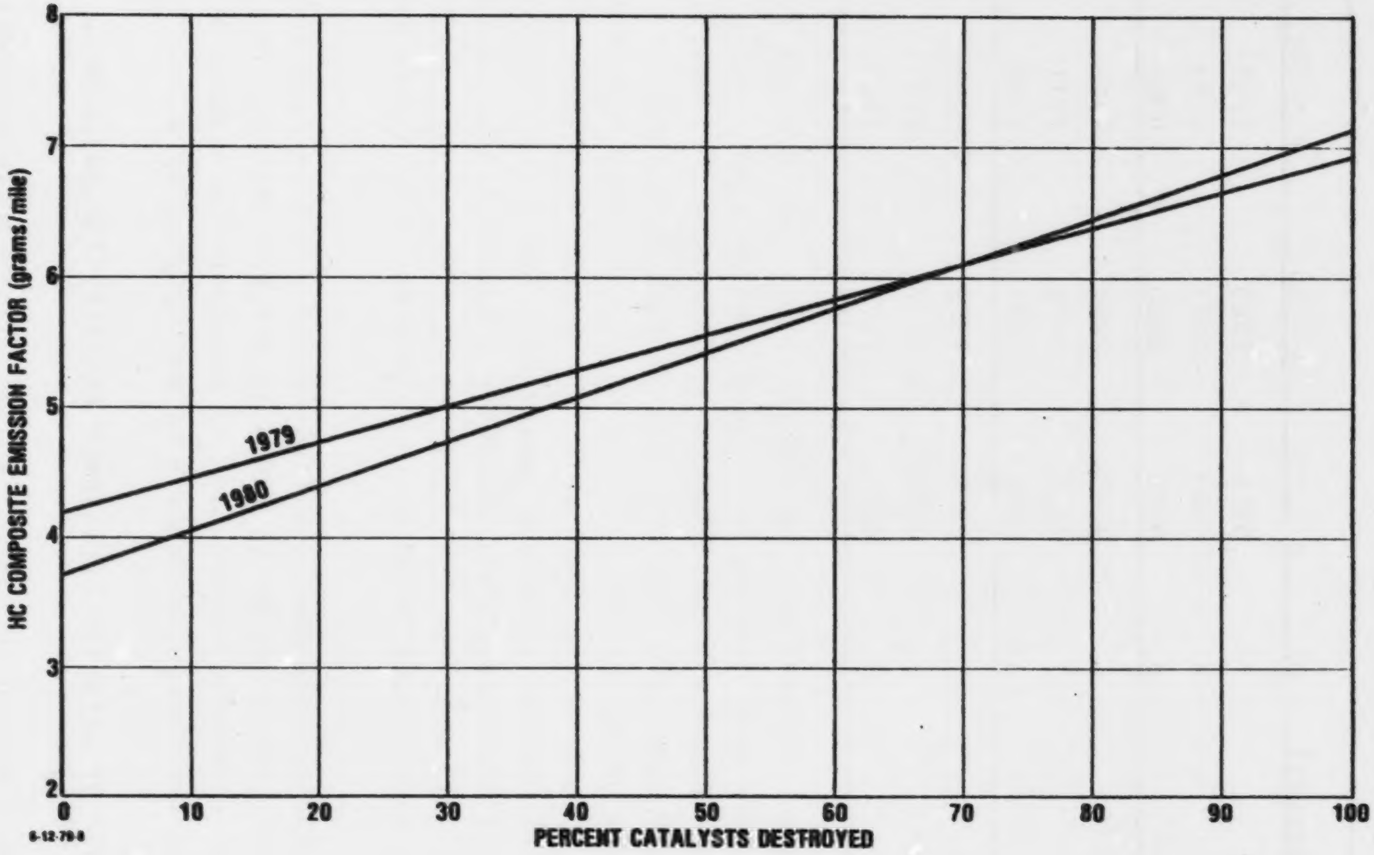

Figure 5. HC COMPOSITE EMISSION FACTOR VS PERCENT CATALYSTS DESTROYED

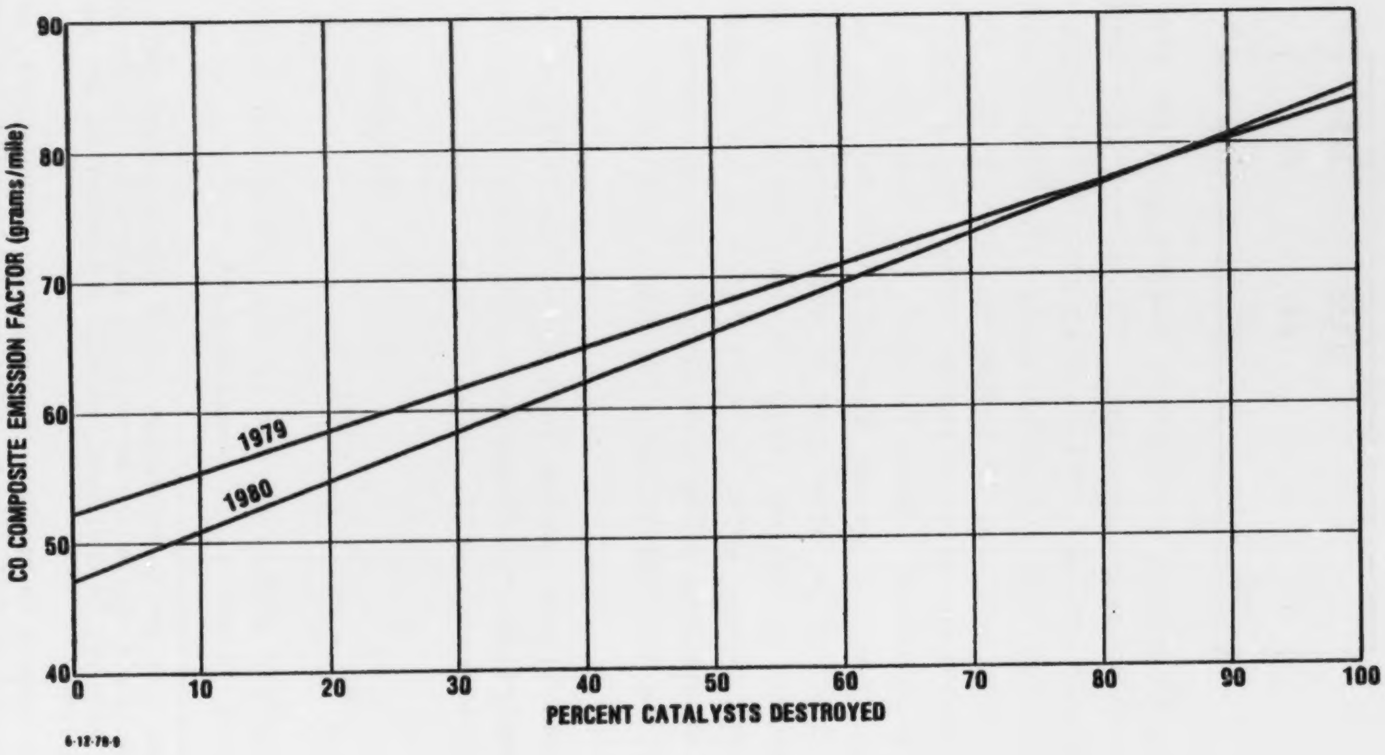

Figure 6. CO COMPOSITE EMISSION FACTOR VS PERCENT CATALYSTS DESTROYED

Table 3. PERCENT INCREASE IN EMISSIONS FOR 100 PERCENT DESTRUCTION OF CATALYSTS

	1979	1980
HC	64	92
CO	60	80

and recovery, following exposure to leaded gasoline and subsequent return to unleaded gasoline. The quoted data imply single or sequential misfuelings, followed by proper fuelings, rather than random misfuelings and refuelings. The latter case is of course of greater interest in a shortage situation. In this section the available data, which as noted, imply sequential misfuelings followed by proper fuelings, will be used to fit an empirical equation. An *assumption* will then be made to the effect that the form so developed is applicable, independent of catalyst history, by interpreting catalyst efficiency as being a *relative* efficiency, which by definition is 100 percent at the time of the misfueling being considered. In all cases, the motorist will be assumed to use unleaded gasoline if it is available.*

The rather sparse quoted data can undoubtedly be fit by a variety of empirical relationships. The one we have chosen, and which works reasonably well, is as follows:

$$E = e^{-km} + (e^{-\gamma m^2} - e^{-km}) \left[1 - e^{\frac{-\alpha(n - m)}{m}} \right] \qquad (2)$$

where E represents efficiency, m is misfuelings, n is total fuelings, and α, γ and k are constants.**

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*Here motorists' beliefs as to whether or not catalysts are destroyed by a single or multiple misfueling becomes all important. If the motorist believes his catalyst is destroyed, he will not return to the use of unleaded gasoline.

**We have not attempted to tie this to air quality calculations, as the data are anecdotal, and in fact, the modeling required becomes far more complex.

Consider first the data cited earlier from the Los Angeles Times. In this case, E represents catalyst efficiency relative to a new catalyst. The first term in Equation (2) involving the constant k describes the expected exponential decay in efficiency immediately following m misfuelings. The second and more complicated term represents the increment in efficiency following (n - m) refuelings with unleaded gasoline. The efficiency E asymptotically approaches the value $e^{-\gamma m^2}$ as $n \rightarrow \infty$. The term in parenthesis $(e^{-\gamma m^2} - e^{-km})$ is the maximum potential increment in efficiency for a given value of m, and the term in brackets is the fraction of this efficiency increment that can be recovered after (n - m) refuelings with unleaded gasoline. The m in the denominator of the exponent in the recovery term derives from the expectation that the rate of recovery would be slower for a greater insult to the catalyst; i.e., larger values of m for the same value of (n - m). The overall behavior is illustrated in Figure 7 where E is plotted as a function of n for $\alpha = 0.20$, $k = 0.75$, and $\gamma = 0.144$, which figures were found to reasonably fit the Los Angeles Times data.

For these coefficients the value of E immediately following m misfuelings, and the asymptotic values of E, i.e., as $n \rightarrow \infty$ are given in Table 4. Note that the asymptotic values E, i.e., $e^{-\gamma m^2}$, are in agreement with the values attributed to Charles Gray in Section 2.2.1. It is interesting to note that for m = 5.2 the equation predicts zero recovery.*

From Figure 7 and Table 4 it appears that a single misfueling, according to this model, is serious from an emissions standpoint but only for a relatively short period of time due to the rapid and appreciable recovery; multiple misfuelings are very serious and remain that way for a long period of time due to the slow and weak recovery.

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*There is zero recovery when $m = k/\gamma$.

Table 4. IMPLIED EFFICIENCY OF MISFUELED AND PARTLY REGENERATED CATALYSTS (PERCENT)

m	After m Sequential Misfuelings	After a Large Number of Proper Refuelings
1	47.2	86.0
2	22.3	56.0
3	10.5	27.0
4	5.0	10.0

The behavior of catalysts following arbitrary misfueling histories is of more interest, but is clearly a complex problem. To illustrate the possible effects, *in the absence of data,* we make the assumption, as already noted, that the efficiency model just developed is applicable to any *catalyst* independent of its history, where E is now defined as being unity at the time of the first misfueling following any random history. This is not completely unreasonable, as behavior of the e^{-km} term has this character; that is, each sequential misfueling reduces efficiency to e^{-k} of the prior value.*

Using the above approach the varying effects of three misfuelings, assuming different shortage histories, were calculated. In the first case, Curve A of Figure 8, a shortage of 5 percent was assumed, which implied one chance in 20 that misfueling would occur; intuition suggested that the minimum damage case would be for equally spaced misfueling. Note that after 60 fuelings and three misfuelings, the catalyst efficiency is 62 percent. Had the shortage been twice as intense (10 percent) for one-half as long (30 fuelings), Curve B would have been followed; after 60 total fuelings, the catalyst efficiency would have been 51 percent. In similar fashion the plot shows results for shortages

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*This entire approach, including the fit of the data quoted in the Los Angeles Times, is obviously tentative. Catalyst efficiency undoubtedly is affected by lead content in the leaded gasoline, the fraction of the tank filled at a given fueling, etc.

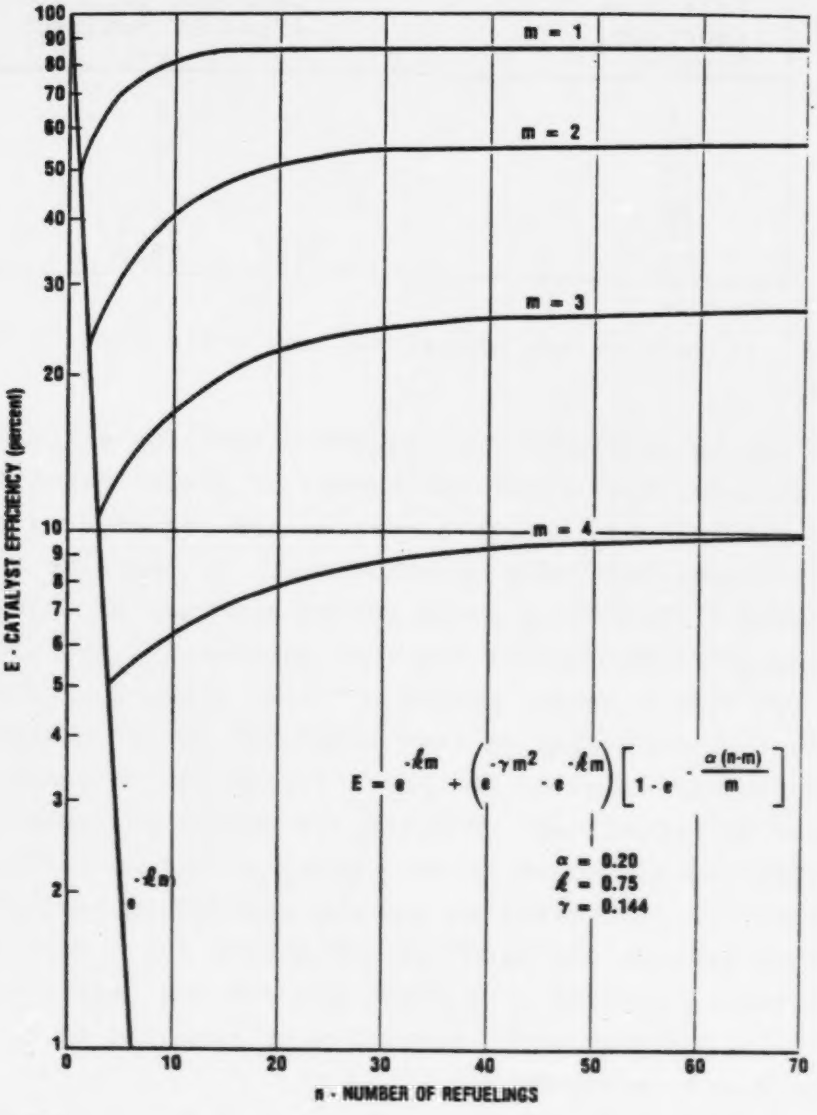

Figure 7. MODEL OF EFFICIENCY RECOVERY OF POISONED CATALYSTS

of 20 percent, 33 percent, and 100 percent (3 consecutive misfuelings), all for a total of three misfuelings. The results after 60 total fuelings are tabulated below:

Table 5. VARIATIONS IN CATALYST EFFICIENCY AFTER THREE MISFUELINGS

Effective Shortage, Percent	Catalyst Efficiency After 60 Fuelings, Percent
5	62
10	53
20	41
33	31
50	25.5
100	26.5

The last two entries are anomalous, and evidently artifacts of the model.

It can be concluded from Figure 8 that for a given number of misfuelings, the larger the number of proper refuelings between misfuelings, the less serious are the effects on catalyst efficiency and hence on emissions. It can also be concluded from Figure 8 that for a given volume shortage of unleaded gasoline, the emission effects are less serious if that shortage is spread out over a longer period of time, e.g., a 5 percent shortage (corresponding to case 1/20) for 40 refuelings is less serious (higher value of E) than a 10 percent shortage (case 1/10) for 20 refuelings. However, it should be remembered that the example chosen above assumed equally spaced misfuelings which probably represents an optimum scheduling sequence. The difference between the catalyst efficiency for a more likely case of random spacing of misfuelings and the case of three consecutive misfuelings could therefore be expected to be less than that indicated in Figure 8.

Hard data to support the model described above is lacking at the present time. Measurements are needed to verify the

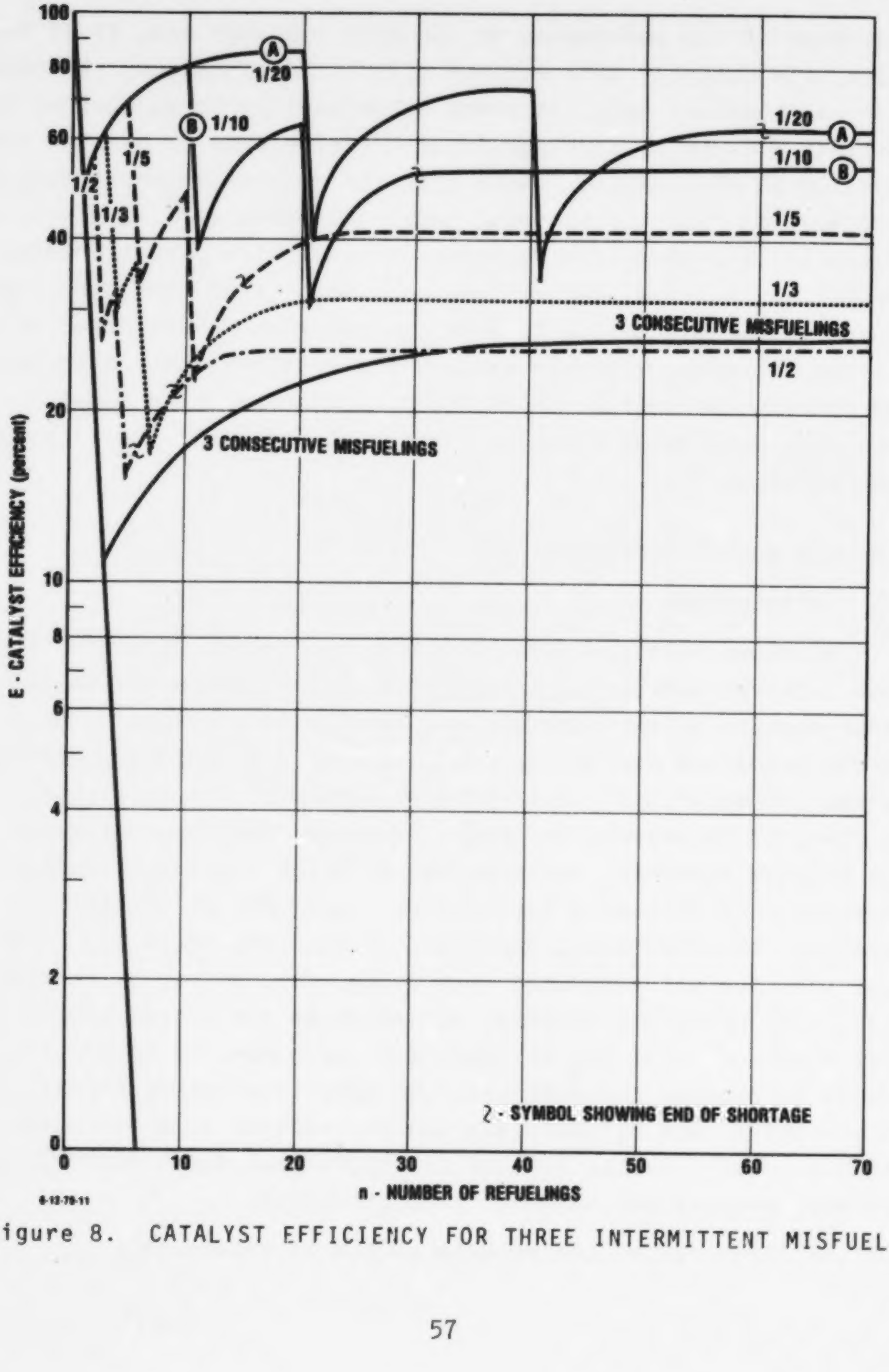

Figure 8. CATALYST EFFICIENCY FOR THREE INTERMITTENT MISFUELINGS

existence of the phenomenon of catalyst recovery and, if it does exist, its behavior with various modes of misfuelings. Without such confirmatory data, it seems inappropriate to go further and estimate effects of shortage-induced misfuelings on average emissions or on air quality. Note that the problem is particularly difficult in that the binomial model described earlier gives the number of catalysts as a function of time which have been mistreated *not* m times, but *at least* m times. Also, in computing recovery, the assumption is that the motorist, once forced to misfuel *by* shortage, will not believe his catalyst to be destroyed and continue to misfuel thereafter. A sophisticated model, with much more data, would be required to take all these factors into account.

3.0 AIR QUALITY EFFECTS

3.1 INTRODUCTION

Previous sections have indicated the extent of misfueling, some catalyst efficiency information, and emission estimates under certain assumptions and certain forcing factors. The shortage-induced misfueling was noted to be potentially serious, as the probabilistic model employed indicated all catalysts, in time, to be exposed to lead. Recovery, however, mitigated the effects somewhat, assuming the motorist returns to using unleaded fuel following random forced misfueling. In these respects, the shortage-induced misfueling problem is more complex than the price-induced misfueling, for, unless price differentials drop, the motorist who misfuels for price reasons will continue to do so; at least for the number of tanksful needed to destroy the catalyst. We make this assumption in this section, and estimate air quality effects in a few cases. Studies of air quality effects for shortage-induced misfueling are more complex and have not been attempted.

We first review the results quoted in Reference 1.

3.2 REVIEW OF THE EPA (REF. 1) RESULTS

Effects on air quality of fuel switching due to price differentials are discussed briefly in Reference 1. The procedures and results are summarized as follows.

First, Nussbaum and Neal compute percentage increases in LDV emissions for 1981, based on their modeling of the Sobotka results coupled with EPA observations, as shown in Table 6.

Table 6. PERCENT INCREASE IN LDV TAILPIPE EMISSIONS DUE TO FUEL SWITCHING PROJECTED FOR 1981 (Source: REF. 1)

	Price Differential, Cents/Gallon				
	0	2	4	6	8
HC	62	11.3	15.4	31.8	57.4
CO	5.1	9.3	12.7	26.2	47.3

The authors then note that LDV tailpipe emissions account for only 16.6 percent of all hydrocarbon (HC) emissions, whereas, for a central business district, 56.0 percent of CO is attributable to LDV emissions. The authors further assume a direct linearity between increases in HC and increases in oxidant. Using these assumption the results in Table 6 yield the figures shown in Table 7.

Table 7. PERCENT INCREASE IN CALENDAR YEAR 1981 AMBIENT LEVELS DUE TO FUEL SWITCHING (SOURCE: REF. 1)

	Price Differential, Cents/Gallon				
	0	2	4	6	8
Oxidant	1.0	1.9	2.6	5.3	9.5
CO	2.8	5.2	7.1	14.7	26.5

The authors note the exponential increase with price differential, and estimate that oxidant would double in 1981 with a

16.7¢ differential and ambient CO levels would double with a 13.02¢ differential.

The above results, as part of an internal memorandum, are obviously intended to give a preliminary indication of the potential severity of the problem, rather than as a definitive treatment. In reviewing these matters, we questioned the assumption of linearity of oxidant increase with HC increase, and were interested in what could be said about the effects of a time-dependent price differential as was shown in Figure 1. We now explore these issues further.

3.3 OXIDANT CHANGES WITH CHANGES IN HYDROCARBON LEVELS

3.3.1 Modeling Approaches

a. General

This is an extremely complex issue, one which has been actively investigated for 25 years or more. Several current approaches used by EPA are described in Reference 6. Much more complex and presumably more accurate approaches exist, in particular that of the Livermore Regional Air Quality (LIRAQ) model, some results from which are given in References 7, 8, and 9. The LIRAQ model was developed for the San Francisco Bay area but has been modified and used elsewhere (W. Deuwer, Lawrence Livermore Laboratory, private communication, April 1979). The complexities (chemistry, photochemistry, meteorology, terrain and insulation) are such that even a sophisticated model such as LIRAQ is best used as an interpolation technique between measured situations rather than as a predictive tool ab initio. Less complex techniques, such as the EPA Empirical Kinetic Model Approach (EKMA) which will be considered here (along with LIRAQ results), clearly involve substantial uncertainties, and again are recommended by EPA as a predictor of relative effects rather than of absolute effects. Other approaches, such as "Appendix J" and "Linear Rollback" (Refs. 6, 7) will not be discussed. "Linear

Rollback" was implicitly used by Nussbaum and Neal in using a linear relationship between hydrocarbons and ozone.

b. The EKMA Approach

The EKMA approach, which is based on smog chamber data, utilizes the curves given in Figure 9. Figure 9 shows maximum afternoon oxidant levels as a function of NO_x and HC content of the air, based on measurements made between 6 and 9 a.m. (but with emissions assumed to continue after 9 a.m.). The isopleths, as noted above, are not considered reliable in an absolute sense; they can, however, be used, along with local data, to estimate percentage reductions in emissions necessary to achieve a particular percentage reduction in oxidant level (Ref. 6).

Perhaps the most intriguing aspect of Figure 9 is the great variation in sensitivity to HC and NO_x changes in different regimes of the plot. At very low NO_x levels, HC levels are largely irrelevant; at high NO_x levels, O_3 changes (percentage-wise) can be greater than the percentage change in HC, as will be shown. In some regions, increases in NO_x at constant HC increases O_3; in others, such increases decrease O_3. (These effects are not necessarily incompatible with LIRAQ results, at least qualitatively.) Clearly, in order to estimate changes in O_3 levels, using the EKMA chart, it is mandatory to locate the starting point, that is, the background condition without misfueling (or with a history of say a 4¢ differential). Backgrounds of course vary with time and place. The following material is exploratory.

c. NO_x-HC Ratios and Magnitudes

Reference 6 gives ambient data (Table 8) for 14 urban and suburban sites, and certain statistics, for non-methane hydrocarbons (NMHC), NO_x and NMHC/NO_x ratios at 0600-0900, both in terms of median values for the period studied and for the five highest O_3 days. The tabulated median NMHC/NO_x ratios on the

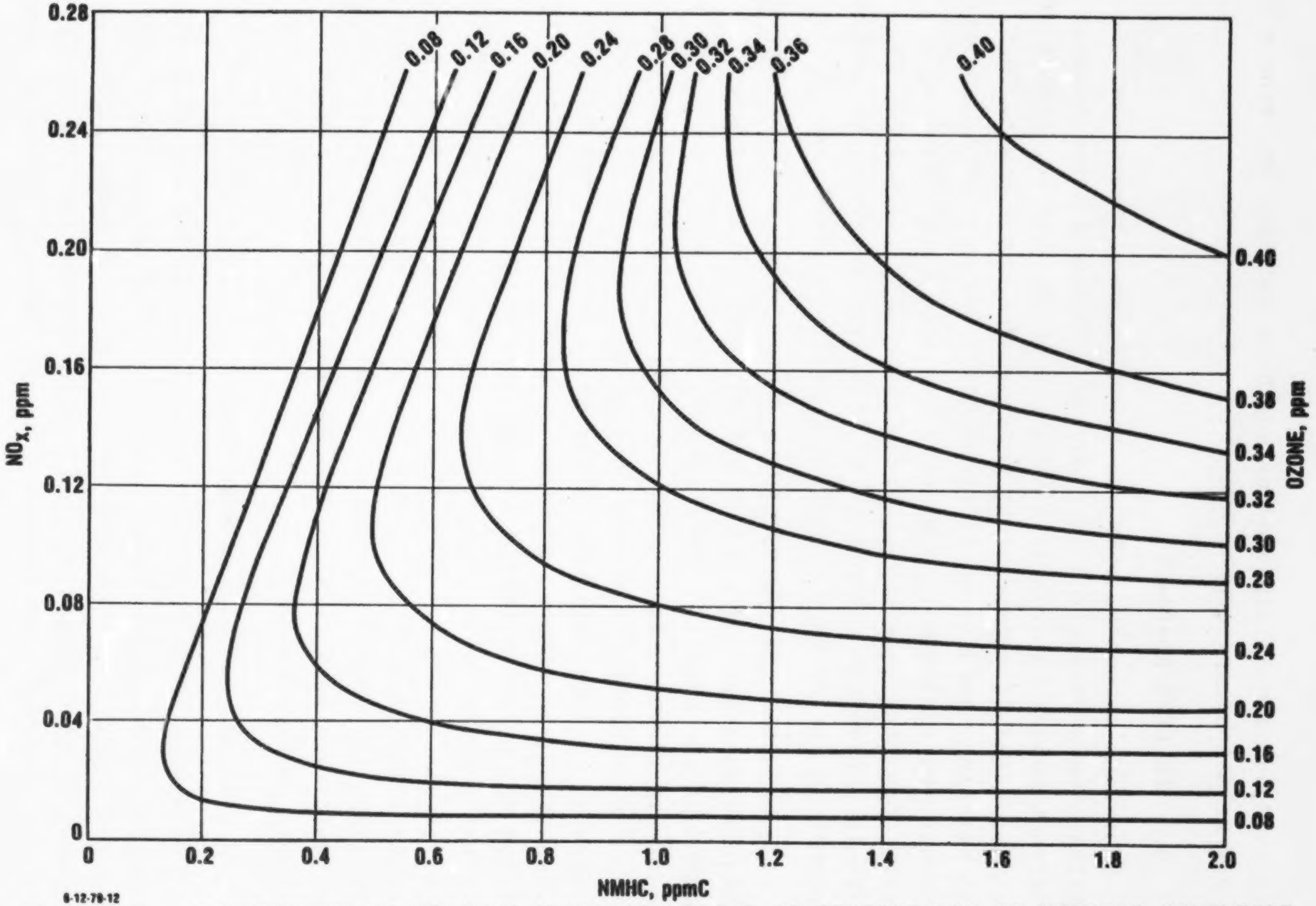

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Figure 9. SENSITIVITY OF MAXIMUM AFTERNOON OZONE CONCENTRATIONS TO MORNING PRECURSOR LEVELS MEASURED UPWIND

Table 8. AMBIENT DATA FOR URBAN SITES OR SUBURBAN SITES NOT DOMINATED BY STATIONARY SOURCES

(1) Site	(2) Sample Size (Days)	(3) Sampling Period	(4) Mean 6 a.m. NMHC, ppmC	(5) Mean 6 a.m. NO_x, ppm	(6) Median NMHC/NO_x Ratio (0600-0900) (Total Period)	(7) Median NMHC/NO_x Rate on Five Highest O_3 Days (0600-0900)	(8) 90th Percentile Ratio (Total Period)	(9) 10th Percentile Ratio (Total Period)	(10) Maximum Observed Afternoon Ozone (ppm)	(11) Remarks
Austin	42	7/1-9/30/75	.27	.026	10.1:1	10.0:1	20.0:1	7.1:1	.10	Station located 8 miles N of CBD
Corpus Christi	44	7/1-9/30/75	.65	.035	18.5:1	21.3:1	37.5:1	10.8:1	.08	Pop = 205,000 w/many, major point sources
El Paso (1)	35	7/1-9/30/75	.59	.067	9.3:1	9.8:1	13.2:1	4.8:1	.15	Station 2-3 mi. S of Franklin Mtn. CBD
Houston (Mae Dr.)	39	7/1-9/30/75	1.14	.156	7.5:1	7.5:1	15.0:1	4.5:1	.20	In heavily industrialized and populated area
Los Angeles	58	7/1-9/30/75	1.48	.147	9.8:1	10.2:1	16.8:1	6.2:1	.25[a]	Station located in Downtown LA
San Antonio	37	7/1- /30/75	.22	.022	11.2:1	7.8:1	33.3:1	6.1:1	.07	Station located 8 mi. NW of CBD
Aldine, Texas	10	7/1-9/30/75	.48	.047	11.9:1	10.0:1	40:1	7.1:1	.21	Houston suburb, 12 mi. N of CBD and 13 mi. NW of an industrial complex
Azusa, CA	86	7/1-9/30/75	1.23	.146	8.5:1	8.0:1	15:1	5.9:1	.32[a]	LA suburban city (25,000), 20 mi. ENE of LA CBD
Canton, OH	20	7/1-7/21/74	.56	.076	7.3:1	9.5:1	13.8:1	4.2:1	.14	Site on Malone College Campus 2 mi. N of CBD
Dayton, OH	16	7/18-8/12/74	.59	.049	12.9:1	11.8:1	23.8:1	8.0:1	.13	Huber Hts. site, 9 mi. NE of Dayton (pop. 243,000) CBD
El Paso (Ascarte Park)	29	7/1-9/30/75	.46	.028	10.0:1	14.0:1	40.9:1	4.0:1	.17	In park, 4 1/2 mi. ESE from El Paso CBD and 3 mi. NE of Juarez, Mexico
Groton, CT	15	7/18-8/21/75	.24	.029	9.5:1	818:1	14.7:1	5.6:1	.18	SE CT, 2 mi. S of Groton-New London (pop. 40,000)
St. Louis	150	6/1-10/31/76	.62	.077	7.6:1	8.5:1	12:1	5.8:1	.24	Composite of 7 Stations located within 4 km of CBD
Washington, D.C.	43	7/1-8/31/76	.62	.086	7.2:1	9.2:1	16.4:1	3.5:1	.15	Camp Station

Source: Environmental Protection Agency, *Uses, Limitations and Technical Basis of Procedures for Quantifying Relationships Between Photochemical Oxidants and Precursors*, EPA-450/2-77-021a, Monitoring and Data Analysis Division, Office of Air Quality Planning and Standards, November 1977, Table 1, p. 24.

[a] Total Oxidant.

five smoggiest days vary from 7.5:1 to 21.3:1; typical values however are in the 8-10 range. These high ratios are in contrast to ratios of NMHC to NO_x from LDV exhaust, or from mobile sources in general.

Thus Reference 5 (Tables I-2 and I-4 therein) can be used to estimate a fleet average emission factor for HC and NO_x. For the year 1980* these composite figures (without fuel switching, or with whatever switching is built into the tables) are 3.73 and 2.66 gm/mile respectively. To the HC figure, evaporative losses of 1.12 gms/mile must be added, as given by Nussbaum and Neal (Ref. 1) for 1980 (which we assume to apply). The total HC emission index is thus 4.85 gms/mile, but only about 85 percent of this is non-methane, leading to an NMHC emission factor of 4.12 gms/mile. The ratio of NMHC/NO_x is thus 4.12/2.66 or 1.55 to 1. With a 4¢ price differential, the NO_x is unaffected but the NMHC rises (Fig. 1) to (4.13 + 1.12)(.85) or 4.46 gms/mile, leading to an HC:NO_x ratio of 1.68. These ratios are far from the 8 to 10 figures quoted above, and, as noted in Reference 1, imply that LDVs are now a minor source of NMHC, even in urban environments.

Additional estimates of total CO, HC and NO_x are provided in Reference 11 (Vol. II, pp. 49-50).

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[1] Estimates for the year 1979 would not be expected to differ greatly.

Table 9. BASE CASE EMISSIONS BY SOURCE, MILLIONS OF TONS/YEAR (SOURCE: REF. 11)

	Automobile[a]		Other Mobile[b]		Total[b]	
	1975	1985	1975	1985	1975	1985
Carbon Monoxide	69.3	32.6	34	29	120	77
Hydrocarbons	7.9	3.5	5	4	28	24
NO_x	4.0	2.7	5	6	22	27

[a] Includes crankcase emissions and fuel system evaporation losses.
[b] As read from bar chart. Totals include stationary sources.

These are evidently nationwide and not urban values. The following are also of interest.

Table 10. HC/NO_x RATIOS (BASED ON REF. 11)

Automobile		Total Mobile		Total	
1975	1985	1975	1985	1975	1985
2.0	1.3	1.4	0.9	1.3	0.9

Reference 7 gives baseline emission data for the San Francisco Bay area Air Quality Maintenance Plan (AQMP) as follows, in tons/day.

Table 11. EMISSIONS IN THE SAN FRANCISCO AIR QUALITY DISTRICT (REF. 7)

	Tons Per Day	
	1975	1985
HC	1013	782
NO_x	696	725

These, like earlier figures, evidently exclude natural sources, but the HC:NO_x ratios are 1.46 and 1.08 respectively.

It is difficult to understand the very high (ca 10) reported ratios of NMHC/NO_x in the EPA tables. The implications to oxidant changes with misfueling are, however, strongly dependent on the ratio, as we now show.

d. Predicted Oxidant Changes

As noted, Reference 6 indicates the EKMA plot should be used for estimating relative changes. We note first, however, that the upper left region of the plot (Figure 9), which corresponds to NMHC/NO_x ratios in the vicinity of 1.5 or so, tends to be unusable, as these ratios tend to be parallel to the oxidant level curves. This regime was found to be unusable in Reference 7 also, and, in fact, where predictions could be made, the measured oxidant values correlated very poorly with the variables used; in short, the plot in this region is evidently not valid in general. Unfortunately it is also in this region that oxidant levels at constant NO_x levels (as we presuppose is the case with misfueling)* appear to be most sensitive to changes in HC level: At the very high level of NO_x of 0.20 ppm for example the curves show a 50 percent increase in oxidant with a 10 percent change in HC.

In order to make what is probably an upper-bound estimate of the effects on oxidant of misfueling (as in Case B, Figure 1) the data in Reference 7 provide additional background. The numbers are from the LIRAQ model, as used for the Bay area for 1985 emissions (HC:NO_x baseline = 1.08).

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*Here we do not include any effects on 3-way catalysts, which are scheduled to be present in a significant fraction of the 1980 model year vehicles.

Table 12. OXIDANT REDUCTION WITH REDUCTIONS IN EMISSIONS

(LIRAQ Results, July 26, 1973 meteorology, 1985 emissions. HC = 782 tons/day, NO_x = 725 tons/day) (Ref. 7)

Percent Reduction HC	0	20	40	60	80
Percent Reduction NO	0	0	0	0	0
Expected Worst O_3, ppm	.189	.140	.082	.069	.055

Note that the natural O_3 levels (0.03 to 0.05 ppm) are being approached at 80 percent HC reduction. Note also the changes in absolute sensitivity to HC reductions, as the first reduction (0-20 percent) in HC reduces oxidant by .049 ppm, whereas the last (60-80 percent) reduces oxidant by .014 ppm. On a percentage basis, however, the reductions are more nearly constant, the first yielding 26 percent reduction and the last 20 percent. On this basis, to crude first order, the procedures used in Reference 1, in which a given percentage change in HC is assumed to equal the same percentage change in oxidant, seems reasonable. It would apply however only where the total HC:NO_x content ratio in the area is of the order of 1 to 1. The absolute increase in oxidant will depend on the proportion of total HC contributed by LDVs. Reference 1 assumes this to be 22.3 percent, of which 74.5 percent is from the tailpipes, leading to 16.6 percent of HC coming from the tailpipes of LDV. On this basis, as an example, a 57.4 percent increase in LDV HC emissions (Table 6) leads to a .166 (57.4 percent) or 9.5 percent increase in oxidant (Table 7). The important point should be made however that, if LDVs constitute a greater percentage of the total emissions, as may be the case for example in Washington, D.C., the increase in oxidant is proportionally larger. (If e.g. 60 percent of the emissions were from LDVs, and the approximation is valid, 57.4 percent increase in HC from LDVs would increase oxidant by 34 percent.)

Now for the Case B (the worse case) assumption in Figure 1, the HC emission factor in 1980 rises to 5.10 gm/mile, from 4.14 gm/mile, assuming a prior 4¢ differential. To both figures should be added the evaporative emissions of 1.12 gms/mile used in Reference 1, yielding 6.22 and 5.26 gm/mile respectively, or an 18 percent increase in HC (and in NMHC). If 22.3 percent of the HC is from LDVs as in Reference 1, then the increase in oxidant at the peak would be 4 percent, increasing however directly with the relative importance of LDVs as emitters. (The procedure assumes however that the total HC:NO_x ratio is near unity, which implies that other sources have HC:NO_x ratios similar to those of mobile sources.)

Returning to the EKMA and the data given in Reference 6, (Table 8) a calculation can be made based on the total NMHC:NO_x ratios measured for various cities. For example, in Washington, D.C. the median NMGH:NO_x ratio on the five highest O_3days (0600-0900) was 9.2:1, or 7.2:1 for the median ratio for the total period studied. The corresponding mean 6 a.m. - 9 a.m. NMHC (ppmC) and NO_x values were 0.62 and 0.086 ppm respectively. (The values for the highest O_3 days are not given.) These values can be used to estimate a percentage increase in oxidant corresponding to a percentage increase in HC. Note again that the great majority of HC must be from non-mobile sources. Thus the tie to LDV must be with the NO_x levels. As an upper bound calculation, we can assume all the NO_x is from LDVs. Using the 1980 fleet average values quoted earlier for the 4¢ differential case, NMHC and NO_x emissions are 4.46 gm/mile and 2.66 gm/mile. At the end of 1980 (Figure 1), assuming a temporary 8¢ differential, the fleet average NMHC rises to 6.22 gm/mile. The corresponding NMHC contributions from LDV, scaling the measured value of NO_x, is $0.086\ (\frac{4.46}{2.66}) = .144$ ppm, and $0.086\ (\frac{6.22}{2.66}) =$ .201 ppm, for an increase in NMHC of 0.057 ppm. The percentage increase in NMHC is thus 0.057/.62 or 9.2 percent. The percentage increase in O_3 in this region can be estimated from the EKMA plot, as follows:

Table 13. INCREASE IN OXIDANT, EKMA MODEL

	NO_x, ppm	NMHC, ppm	O_3,[a] ppm	Increase, Percent
Base (4¢)	.086	.62	0.209	Base
8¢	.086	.677	0.215	2.9

[a] Interpolating and assuming linearity in HC.

The maximum increase in O_3 on this base is 2.9 percent. As only a fraction of the NO_x can be from LDVs, this approach would imply the temporary 8¢ differential would lead to perhaps 1 percent - 2 percent increase in oxidant. The significance of this is most evident if the number of days exceeding specified levels is estimated.

These procedures are clearly too crude for anything but very preliminary estimates. However, it appears that using available data and EPA procedures and models, the increase in oxidant resulting from a temporary 8¢ differential (vs an assumed prior value of 4¢) is in the 1 to 4 percent range, declining very slowly after reimposition of a lower maximum price differential.

3.4 EFFECTS ON CO

The CO case is much simpler, since CO is directly released by autos rather than being formed, as in oxidants, by complex chemical reactions. Reference 1 indicated 56 percent of the CO (for 1981, but the year does not appear to be critical) to arise from LDV emissions. On this basis, along with Figure 2, the peak increase in CO emissions would be .56 (61.5 - 51.5) or 5.6 percent for the price differential history shown in Figure 2.

Much larger emission and oxidant changes can arise from the potentially larger effects of shortages, as was shown in Figures

5 and 6. Qualification of this effect, however, would require considerably more study and scenario definition.

4.0 CONCLUDING COMMENTS

The quality of the available data, the many uncertainties in the modeling approaches, and the preliminary nature of the analysis all preclude drawing hard conclusions from the preceding analysis. Nevertheless, we believe the following points are worthy of comment.

1. Shortages, over a sustained period (6 months to a year), of unleaded gasoline relative to leaded gasoline can lead to severe misfueling, and massive degradation of the effectiveness of catalytic converters present on light duty vehicles. Eventually, on a statistical basis, all catalysts would be subjected to misfueling.

2. The effects of a shortage may be mitigated by catalyst recovery effects, *if* drivers are aware (and the facts support) that refueling with unleaded gasoline leads to some catalyst recovery. No such recovery will occur if motorists believe that one or so misfuelings lead to permanent catalyst destruction.

3. An available EPA model showing misfueling rates due to price differential was developed in a time of relatively ample supply compared to the present. Results may be misleading under shortage circumstances such as now exist. Interaction, not thoroughly understood, may be of great importance. Thus, should a mandated small price differential lead to a shortage, the overall misfueling rate could increase. Conversely, a large price differential could lead to misfueling under shortage conditions.

4. If differential price-induced misfueling behavior is as indicated in the EPA model, and driver response time (the period before action is taken following an increase in price

differential) is moderate (a few months or less), then a six-month differential price rise to, say, 8¢ leads to long term effects in terms of damaged catalysts and little difference would be noted thereafter whether reimposed price differentials are 0¢ or 4¢.

5. Air quality effects of misfueling are not linear in misfueling rates, effects apparently being dampened by large emissions of hydrocarbons from other sources.

6. If, as reported, 3-way catalysts are far more sensitive to misfueling than are current catalysts, the effects of shortages will be greatly aggravated once 1980 model cars enter the fleet.

7. A great deal more data is needed on catalyst effectiveness vs throughput of varying amounts and spacings of leaded gasoline (of various lead content). Such data are essential where hard policy choices must be made.

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USE OF ADDITIVES AND BLENDING AGENTS TO INCREASE THE UNLEADED GASOLINE SUPPLY

Robert C. Oliver

INTRODUCTION

As discussed elsewhere in this report, shortages of unleaded gasoline, when leaded gasoline is available, can lead to severe misfueling problems. It is thus of interest to examine some of the alternatives which might increase the supply of total gasoline, and more critically, the relative supply of unleaded vs. leaded gasoline. The alternatives to be discussed include use of MMT* as an additive, various alcohols and ethers as blending materials, and a speculative regulatory approach involving control of pool average and leaded gas lead contents. In the MMT case, which appears to be the most viable, a discussion of emission tradeoffs is included.

Approaches, which might lead to an increase in crude, through relaxation of power plant emission standards, fuel substitution, or other means, while quite possibly significant, are complex issues and not explored here. Similarly, purely economic approaches, which induce the refiner to increase unleaded output, are not included.

MMT

MMT is an octane-raising manganese compound, effective in very small quantity, which was used in much of the unleaded gasoline sold prior to September 18, 1978, at which time EPA ruled

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*MMT is methyl cyclopentadienyl manganese tricarbonyl ($CH_3C_5H_4Mn(CO)_3$). Its theoretical manganese content is 25.2% by weight. Ethyl quotes 24.4% (Ref. 24).

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against its continued use in view of questionable effects on auto emissions (Ref. 1). The ban has since been lifted (May 30, 1979), by an EPA announcement that the ban temporarily* will not be enforced. The action follows a recent request by an industry group (Ref. 3) for a temporary waiver to permit its use, at the 1/32 gm Mn/gal level, which is roughly half the maximum content used previously. The discussion which follows, while relevant to this decision, also provides information which may be of value in deciding whether to extend what is now a temporary suspension of the ban.

MMT is manufactured by the Ethyl Corporation; it is roughly twice as expensive as tetraethyl lead in increasing octane (Ref. 2). It can be used in either leaded or unleaded gasoline, but has been of most interest where lead is prohibited. In 1978 the MMT content of unleaded gasoline (averaged over all unleaded gasoline) was reported to be about 0.03 gm (manganese) per gallon (Ref. 1, Ref. 3); i.e., about the same as the level recently requested. However, not all unleaded gasoline at that time contained MMT and various refiners used varying MMT contents; Ethyl recommended against use above 1/8 gm Mn per gallon (Ref. 2). EPA's ruling against its continued use, in September 1978, stated that Ethyl Corp. had failed to prove its contention that MMT at the 1/32 to 1/16 gm Mn/gallon level would not adversely affect emissions (Ref. 1). The auto companies, following tests on MMT-containing fuel at the 1/8 gm Mn/gallon level, had found increases in emissions and catalyst "plugging," and (Ref. 4) were obviously concerned that MMT use would reduce catalyst life to below the required 50,000 miles. Concerns were particularly evident (Ref. 1) for 1979 cars, designed to meet a 0.41 gm/mile hydrocarbon standard. Ethyl Corp. (Ref. 1) argued that data at 1/8 gm/gallon are irrelevant and that effects on emissions are greatly reduced at the lower MMT levels which had been in actual use; also earlier had indicated they had no evidence that MMT causes plugging of catalytic converters (Ref. 4). This latter contention does not seem to be in dispute at EPA (Ref. 5); the EPA argument, however, seems to be that MMT, for which no scavenger is known, raises engine-out emissions, and assuming fixed percentages of these emissions are removed by the catalyst, thereby increases tailpipe emissions. Just how much increase results, over what time periods and at what MMT contents, seems to be uncertain. Ethyl (Ref. 6) in very recent discussions, argues that the increase in hydrocarbon emissions would be no greater than 0.1 gm/mile in any case and might well be less.*

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*Until October 1, 1979.

MMT, as does tetraethyl lead, increases octane number non-linearly with amount. The following numbers are from Ethyl Corp. (Ref. 7) for use of MMT in unleaded regular:

gm/gal Mn	Δ Research ON	Δ Motor ON
1/32 (0.031)	1.2	0.7
1/16 (0.062)	1.7	1.0
1/8 (0.125)	2.5	1.5

These figures are not inconsistent with other sources, which indicate that 1/32 gm/gallon of Mn raises octane (presumably (R+M)/2) by 0.9 units (Ref. 8).

MMT can be used in unleaded gasoline to increase supply at constant octane number, or to increase octane number at constant supply, or to release other materials, in particular toluene, for use in petrochemicals (theoretically, a granting of the 1/32 gm waiver would release 2 billion gallons of toluene now used to upgrade the octane of unleaded gasoline (Ref. 8)). The first alternative is of particular interest here, as the industry group requesting the waiver argues that 338,000 bbl/day of "additional production" (Ref. 3) at constant crude run would result. The meaning of this figure is unclear; the same article (Ref. 3) quotes other sources to the effect that relaxation of the ban would result in 120,000 to 200,000 bbl/day of additional "production."*

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*See Ref. 25, received after preparation of this material, which documents this statement.

It should be noted that the supply of MMT may not quite be adequate at the 1/32 gm/gallon level, if all unleaded gasoline is treated. The total required, assuming 50 billion gallons/year of unleaded gasoline (which may be high), would be about 13.7 million lb/yr, whereas Ethyl quotes "capacity" at 12.6 million lb/yr (Ref. 3). Ethyl states also, however, (Ref. 7) that facilities "in place" could produce about 10 million lb/yr, which would permit treatment of all unleaded gasoline "at the 0.02 to 0.03 gm/gallon level."

It may turn out, of course, that not all refiners will choose to use MMT.

The perhaps temporary use of MMT as an additive has interesting implications in terms of total emissions in a supply-short (and/or octane-short) situation. This is because emissions in all cars using unleaded gasoline will presumably increase somewhat due to the MMT, but the number of poisoned catalysts due to shortage-induced misfueling should also be reduced, decreasing the emissions which would have resulted from catalyst destruction had MMT not been added. The trade-offs are, in fact, time-dependent, but some perspective can be gained with a few sample calculations as follows.

Assume MMT increases hydrocarbon (HC) emissions by 0.1 gm/mile on all cars using unleaded gasoline. Assume further that 100,000 additional bbl/day of unleaded gasoline would be made available, increasing the unleaded gasoline supply by 3 percent. Assume that the typical motorist fuels his car 20 times during the shortage period and that three misfuelings are required to destroy the catalyst.* The reduction in shortage-induced misfueling depends on the baseline shortage; several values can be considered:

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*It subsequently has become clear that the additional unleaded gasoline production comes from leaded gasoline production. (See Volume I,

Case	Shortage Without MMT	Percent Catalysts Destroyed	Assumed Shortage with MMT	Percent Catalysts Destroyed	Reduction in Catalysts Destroyed
1	10%	31.0	7%	16.0	15.0
2	7	16.0	4	4.5	11.5
3	4	4.5	1	0.0	4.5

If it is assumed that 50,000,000 catalyst equipped LDVs are involved, each fueling is 10 gallons, average miles per gallon is 15, and incremental HC emissions are 0.1 gm/mile, the total increase in HC emissions during the 20-fueling period is 20x10x15x50,000,000x0.1 or 1.5×10^{10} gm (15,000 metric tons). (These emissions would presumably discontinue if MMT is then removed, but this may be unlikely.) The corresponding increase due to misfueling in emissions over the time period assumed is obviously an integral,* increasing as it does with time as shortage-induced misfueling occurs. The rate, however, at the end of the period, if the shortage should be eliminated, would continue indefinitely, so that the rate at the end of the period is of interest.

The average HC emissions from catalyst-destroyed cars can be estimated from EPA data, as about 6 gm/mile, or 4 gm/mile greater than from normal tailpipe emissions (Ref. 9). The corresponding increase in emissions, for the 20 fueling period *subsequent* to that of the shortage would then be, on the same basis, 0.15 x 4 or 0.6 gm/mile for the catalyst-equipped fleet for the first case, 0.46 gm/mile for the second case and 0.18 gm/mile for the last case. These are all larger than the maximum 0.1 gm/mile increase estimated by Ethyl Corporation for vehicles burning MMT-containing gasoline. Corresponding total HC emissions are 9×10^{10} gm, 6.9×10^{10} gm, and 2.7×10^{10} gm. (Respectively similar effects would be expected for carbon monoxide emissions.) What the above figures indicate is that with MMT in the unleaded gasoline, the increase in HC emissions in a period of 20 fuelings would be 15,000 tons; without MMT, the increase would be 27,000 to 90,000 tons, in the same subsequent 20-fueling period (and continuing thereafter), assuming, as a best situation, that the shortage in the subsequent period becomes negligible.

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*This calculation, based on an EPA approach to the misfueling issue (see Cutchis/Oliver paper, this volume) ignores the possibility of catalyst regeneration following misfueling and in this aspect is thus favorable to the MMT case. The assumed reduction in shortage is, however, at the low end of the estimated range. More accurate information is obviously needed.

** HC emissions from cars using MMT-containing unleaded gasoline are presumably also time-dependent; for purposes here, however, the 0.1 gm/mile increment is assumed to begin with first use and to remain invariant thereafter.

While the set of figures used above may have no firm quantitative significance, the implication that reduction in leaded gasoline shortages by use of MMT could have beneficial air quality impact is believed to be correct. The conclusion becomes increasingly firm (by these models) if the increased shortage in the absence of MMT extends over a longer period; if a finite shortage extends indefinitely, however, the catalysts (by these models) are all eventually destroyed and the argument becomes moot.

MMT - TETRAETHYL LEAD MIXTURES

MMT was originally promoted (Ref. 10) for use in conjunction with tetraethyl lead, and argued to promote the effectiveness of tetraethyl lead itself. Unleaded gasoline is defined for EPA purposes as gasoline having less than 0.05 gm/gal of lead which is not necessarily the same as permitting 0.05 gm/gal of lead. A plausible question might thus be whether an MMT-lead mixture, at levels of the order of or under 0.1 gm (metal)/gallon, might increase octane, reduce shortages, and beneficially affect air quality by reducing shortage-induced misfueling to a greater degree than would MMT alone.* (Typically, 0.05 gm of lead per gallon increase octane number by about 0.5 unit.) Unfortunately no catalyst deactivation data, nor supply improvement data, seems to be available for this option. Lengthy research would probably be required to get the needed data. This option thus cannot be considered for the near term, and is not discussed further here.

ALCOHOLS AND ETHERS**

Methanol and ethanol are miscible with gasoline to a limited extent, particularly in the absence of water contamination, and (particularly ethanol) have long been considered and used to some extent to extend gasoline supplies. These materials can also be used in pure form as motor fuels. Higher alcohols are more miscible with gasoline, and one, tertiary butyl alcohol (TBA), has been used in substantial quantity (up to 7 percent) by at least one refiner (Atlantic Richfield) since 1973; Mobil has also been using at least some TBA (Ref. 11). TBA is made using isobutylene as a feed stock. The same material can be used to make the corresponding methyl ether, methyl tertiary butyl ether (MTBE), which has a higher blending octane number, as illustrated by the following:

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*Note that catalyst deactivation following leaded gasoline usage may result from (or partly from) the bromine or chloride scavengers (ethylene dibromide or dichloride) which are used with lead, rather than being entirely from the lead itself.

**For reference, the following formulae may be of interest:

methanol	CH_3OH
ethanol	CH_3CH_2OH
tertiary butyl alcohol	$(CH_3)_3C{-}OH$
tertiary butyl methyl ether	$(CH_3)_3C{-}O{-}CH_3$
tertiary amyl methyl ether	$(CH_3)_2C(CH_3{-}CH_2)O{-}CH_3$
toluene	$CH_3C_6H_5$
benzene	C_6H_6

Compound	Research Octane Number (Ref. 11)	Research Octane Number (Ref. 7)	Motor Octane Number (Ref. 7)
MTBE	115	117	101
TBA	108	109	97
Toluene	110*	115	97
Benzene	106*	-	-
Catalytic Cracked Gasoline	92	-	-
Straight Run Gasoline	70	-	-

*These figures differ from those for the pure hydrocarbons. Thus Guthrie (Ref. 11a) gives 120.1 RON and 103.5 MON for pure toluene, and 114.8 MON for pure benezene. Blending octane numbers differ with base stream, and may be considerably higher in leaded gasoline.

Another methyl ether, tertiary amyl methyl (TAME), alone or in mixture with MTBE, has also been suggested. Blending octane numbers for these two materials are quoted as follows in Ref. 12:

Compound	Blending Octane Numbers*	
Compound	Research	Motor
MTBE	118	101
TAME	112	99

*with typical unleaded gasoline

Intense interest in MTBE has come about following the granting of a waiver for its use (up to 7 percent) in unleaded gasoline in February 1979, following application by Atlantic Richfield. A number of companies have recently announced plans for production of MTBE; further discussion is provided later herein.

Without going into extensive detail on these materials, it appears that two principal routes are open to use of alcohols or alcohol-based materials in unleaded gasoline. The first of these involves direct use of ethanol in blends with gasoline at about the 10 percent level ("gasohol"); the second utilizes methanol in chemical combination with isobutylene or isoamylene to form MTBE or TAME. The question then arises whether these materials can have any significant effect on gasoline supplies over the near term (6 months to a year).

As a point of departure, it must be recognized that these materials are fuels first and octane improvers second. That is, to increase the octane number ((R+N)2) of an unleaded gasoline ignoring changes in butane needed to adjust vapor pressure,* (from 86 to 87), through use of MTBE, 4.3 vol percent of MTBE must be added; in contrast MMT requires about 0.001 percent, (in effect MMT has a blending octane number of the order of $4x10^4$). And, since addition of 1/8 of a gram of MMT (1/32 gm Mn) to all U.S. unleaded gasoline, which increases, as noted earlier, octane about this same amount, would require some 12,000,000 lb/year of MMT, the volume of MTBE required to correspondingly affect octane can be appreciated.

For further perspective production of unleaded gasoline in the United States is, or should soon be, of the order of 3 million bbls/day or about 50 billion gallons per year, or about 3.5×10^{11} lb/year.

Turning now to the supply of methanol, the 1979 production was 1.1 billion gallons, the current capacity being 1.25 billion gallons per year (Ref. 13). The material is made from natural gas (CH_4) by partial oxidation and subsequent reaction of carbon monoxide with hydrogen at high pressure. (Methanol is an alternative to LNG as a means of shipping natural gas from regions where natural gas is currently in surplus.)

Current spot prices for methanol (CH_3OH) are 46 to 63¢/gallon, with much lower prices projected by some analysts as being possible for methanol produced from coal (e.g., 15¢/gallon) (Ref. 13). As the use of methyl ethers in gasoline has only recently been approved, it is doubted that much of the referenced 1.1 billion gallons is intended for gasoline use. However, 1.1 billion gallons per year could in principle (ignoring its reduced fuel value) provide up to about 2 percent effective increase in unleaded gasoline. (A group in California is studying the feasibility of using methanol-gasoline blends in current autos (Ref. 14).)

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*Gasoline must meet numerous specifications, of which two, octane number and vapor pressure, are involved here. Thus, if a blending agent suppresses vapor pressure, additional butane (or other volatile ingredient) must be added; if it increases vapor pressures less butane can be used. (Ref. 7) (See also footnote p. 85.)

Production capacity for MTBE is building up rapidly, but "significant" quantities will not be available for six months to a year, and even those quantities will not have much effect. Thus Petro-Tex has a plant under construction to produce 617 million lb/yr to be on stream in 1980 (Ref. 15); Atlantic Richfield is to have a 440 million lb/yr plant on stream in January 1980 (Ref. 16), and other producers are undoubtedly giving it consideration.* Production plans for TAME, if any, have not been noted. An estimated total capacity for MTBE in the next few years can be inferred from Ref. 3 as being of the order of 12,000 bbls/day, or 1.3 billion lb/year.** This figure represents about 0.4 percent of the unleaded gasoline production. Obviously, however, much could be made if all available isobutylene were to be used, which could be up to 3 percent of the U.S. gasoline pool (Ref. 12). This is of course unrealistic, as markets already exist for materials such as isobutylene. In fact the net gain in unleaded gasoline through production of MTBE and similar materials is in doubt, as isobutylene is used to make TBA, production of which may decline, or historically, alkylate gasoline, a high octane conventional gasoline component; also MTBE in fact is itself considered as a material which can displace toluene, now in heavy demand for unleaded gasoline, for other markets.

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*Phillips Petroleum began production of MTBE in April 1979 (Ref. 16a) at unspecified rates.

**Ref. 16b gives 1.4 billion lb/yr.

In terms of octane boosting capacity, and again ignoring small vapor pressure effects,* MTBE, at 110 octane $(\frac{R+M}{2})$, and at 1.3×10^{9} lb/yr, if added to an 87 octane ((R+M)/2) unleaded gasoline pool at 3.5×10^{11} lb/yr (0.4 percent), would increase the pool octane by $(110-87) \times (1.3 \times 10^{9})/3.5 \times 10^{11}$ or 0.09 octane units. If octane were held constant, this could also yield a volume increase, which (prorating the figures estimated for MMT) could yield an additional (0.09/.9) x 100,000 or 10,000 bbls/day (about 0.3 percent). The total gain, in the absence of butane vapor pressure adjustment, might be about 0.7 percent. This is not negligible, but as noted is also quite uncertain, as MTBE may, depending on economic factors, simply release toluene, leading to no gain in volume of unleaded gasoline.

The alcohol blend which has received the most attention in recent years, and in fact on which many years of experience exist,is typically a 10 percent blend of ethanol in gasoline; known as gasohol. Gasohol is currently being marketed in Nebraska, Virginia (Ref. 17), in Wheaton, Maryland, and elseelsewhere.

Gasohol enjoys considerable political and other forms of support, such as exemption from the 4¢/gallon federal excise tax, which assuming 10 percent ethanol in the blend, corresponds to a 40¢/gallon subsidy on ethanol or $16.80 subsidy per ba (Ref. 18), plus a $2 per barrel direct Department of Energy (DOE) subsidy, for a total of $18.80/barrel of ethanol.

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*Ethyl (Ref. 7) gives octane gains for a 5 percent addition of blending agents as follows, including butane adjustments:

Net Octane Gains for 5 Percent Addition of Blending Agents

	Butane Credit, Percent	O.N. Gain Due to 5 Percent Addition			
		Unleaded Regular		Leaded Regular	
		RON	MON	RON	MON
Toluene	1.071	1.07	0.69	1.34	1.13
MTBE	0.347	1.16	0.84	1.44	1.17
TBA	NONE	0.78	0.63	0.70	0.85
Ethyl Alcohol	-2.347	0.80	0.17	0.63	Negative

Subsidies at the state level also exist. DOE has also, as a separate issue, ordered Amoco Oil Company to provide one gasohol producer (American Agri Fuels) with as much unleaded gasoline as it needs through May 1980, which could amount to 1.4 million bbls (Ref. 19). These subsidies, as well as enforced supply availability for the gasoline component, make gasohol profitable even with alcohol costing as it now does $1 to $1.30 per gallon (Ref. 20).

Ethanol improves octane non-linearly, its blending value varying with concentration. One source, which should be authoritative gives an octane number of 125 relative to an 85 ON base material (Ref. 21), at the 20 percent level. These octane ratings are high compared with data of the Ethyl Corporation (Ref. 7) who give 110 Research Octane Number and 90 Motor Octane Number for ethanol.* Ethanol can be used up to about 40 percent, if anhydrous. The mixture of gasoline and alcohol separates into two phases if too much water is present. This phase separation is stated to be apparently more of a problem to the blender than to the motorist, as precautions the motorist must take are evidently not very bothersome (Ref. 21).

Various figures are quoted for the potential of gasohol. Of interest here is the near term situation. The distillation industry is not capable of producing some 100,000,000 gallons of ethanol per year, little of which is used for gasohol (Ref. 20). About a million barrels (42 million gallons) of conventional gasoline have been replaced by gasohol in the past few years (Ref. 18), implying a usage of 100,000 bbls (4.2 million gallons) of alcohol. A DOE study (Ref. 18) suggests that alcohol fuels could reduce annual U.S. demand for unleaded gasoline by 10 billion gallons, 9 percent of today's consumption. This appears to imply that all gasoline would be blended with ethanol.

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*See also tabulated data on footnote, previous page.

Ethanol in the foregoing discussions is assumed to be produced by fermentation. Ethanol (industrial grade) can also be produced petrochemically by hydration of ethylene. Ethanol can also be produced from various waste materials (Ref. 18).

Emission data on alcohol and other blends is spotty, and dependent on the manner in which the fuels are used. Methanol and ethanol apparently increase aldehyde output, and these contribute to smog. Alcohols however can permit reduction of aromatic content; as aromatics are believed to be weakly carcinogenic, the net effect may well be beneficial.

Returning to the question of near term effects on supply, it can be noted that 100,000,000 gallons of fermentation-derived ethanol per year, if it could all be used as gasoline equivalent (creating a "dry" nation), would increase the unleaded gasoline supply by 6500 bbls/day, or 0.2 percent. Minor additional benefit would be achieved from the octane enhancement. As only a small fraction of this alcohol could be so diverted[1] the potential near term effect of ethanol on supply shortages seems to be very small. The same can be said for direct use of methanol (which also involves more technical problems) and also the various methyl ethers.

LEAD ALKYLS

Reduction, and eventual elimination, of lead in gasoline, has been an EPA goal for a number of years, but various events have led to delays in the original plans. The latest of these was on April 5, 1979, when President Carter announced that a phasedown to 0.5 gm/gallon, scheduled for October 1, 1979, would be delayed for one year, with a 0.8 gm/gallon value substituted (Ref. 22). The statement was made that the original phasedown, if fully implemented, would reduce gasoline by 350,000 - 450,000 bbls/day, and refinery crude runs would increase by 30,000 to 60,000 bbls/day. Substitution of the 0.8 gm/gallon values would, it was stated, avoid 75 percent of the loss, while still protecting the urban environment from the effects of lead.

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[1] The amount which could be so diverted is obviously a matter of price, and thus related to the subsidy.

The significance of the 0.8 gm/gallon order will depend on the details of its enforcement.[1] Thus the industry was originally scheduled to meet the same 0.8 gm/gallon level in January 1978, but various waivers have been granted, so that the overall average has remained considerably higher. In April 1979, the pool average lead content was estimated (Ref. 23) by EPA to be 1.3 gm/gallon, with leaded gasoline being in the 2.0 to 2.2 gm/gallon range.

Lead alkyls (tetraethyl or tetramethyl) increase octane non-linearly (an effect already noted for MMT), with the first increment being most effective, and declining thereafter. The response of octane number to lead addition (the susceptibility) varies with the type of the base material. While the tradeoffs are complex, and vary for each refiner, the addition of lead has generally been found to be the lowest cost means to increase octane. The non-linearity of the increase with the amount added however means that addition beyond certain levels is not profitable; in motor gasolines this level has been about 3 gm/gallon.[2] (Aviation gasolines use up to 4.5 gm/gallon.)

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[1] The EPA (Ref. 24) in early June, 1979 announced that three guidelines are involved. To quote Ref. 22, "Under the relaxed lead standards, the EPA will set three guidelines. From now until October 1, all refiners will be freed from meeting the current limit of 0.8 gram of lead per gallon of gasoline. About 75 percent of the refiners already have been granted such waivers.

Then, on October 1, the refiners will be eligible for a one-year deferral of the previously scheduled new lead limit of 0.5 gram per gallon, provided at least 45 percent of their gasoline output is unleaded or they increase the unleaded share of the current 0.8 gram standard until October 1, 1980, and 0.5 gram thereafter."

[2] A Surgeon-General imposed 4 gm/gallon limit exists for motor gasoline.

The non-linearity of octane response to lead addition has interesting implications which may affect the relative supplies of leaded and unleaded gasolines. In essence, this non-linearity means that a refiner can produce more "octane-barrels" (average octane x barrels produced) per day (and possibly more profit) by adding say 1 gm/gallon of lead to all gasoline rather than adding 2 gm/gallon to half of the product and none to the other half.

The situation is illustrated qualitatively (and simplistically since only 2 gasolines, leaded and unleaded, are assumed) in Figure 1a, b, and c. In each figure the yield of total (leaded plus unleaded) gasoline is plotted vs lead content in the leaded gasoline product (of which there may be none). The differences between Figure 1 and 2 are intended to show that a complex refinery can minimize the yield loss in making unleaded gasoline relative to a simpler refinery, at however greater processing cost. Figure 3 is for a "typical" refinery which, in view of the processing cost argument, could also indicate net revenues for either the complex or simple refinery (under the assumed differential pricing constraints and seller's market conditions).

Figure 3 gives hypothetical lines of total yield, pool average lead content and the split between leaded and unleaded gasoline. Note that for any given split between leaded and unleaded gasoline (excluding the 0 percent leaded case) the total gasoline yield, and thus the unleaded gasoline yield, increases as more lead is put in the leaded gasoline. For any given refinery average lead content (the Pb lines) however--an EPA type constraint--the total gasoline yield is maximized, as noted earlier, by producing only leaded gasoline with the refinery average lead content. The net profit, under a seller's market and mandated price differential situation *may* follow the same trend. A refiner, in short, might find it profitable to move from a point at A, in which a pool average lead content of 1.5 gm/gallons is met by producing 37.5 percent leaded gasoline containing 4 gm/gallon of lead, and 62.5 percent of unleaded

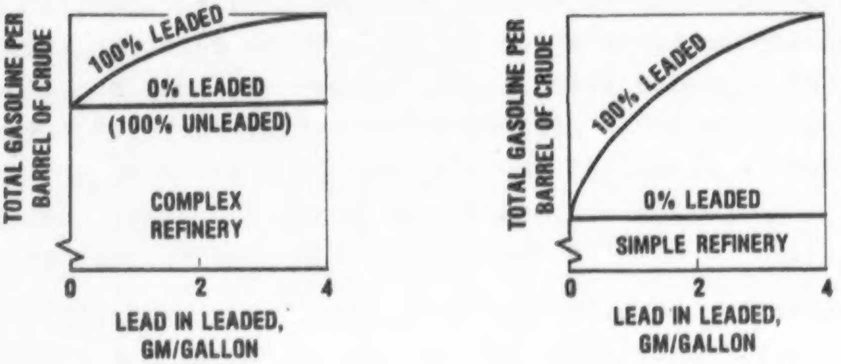

Figure 1a

Figure 1b

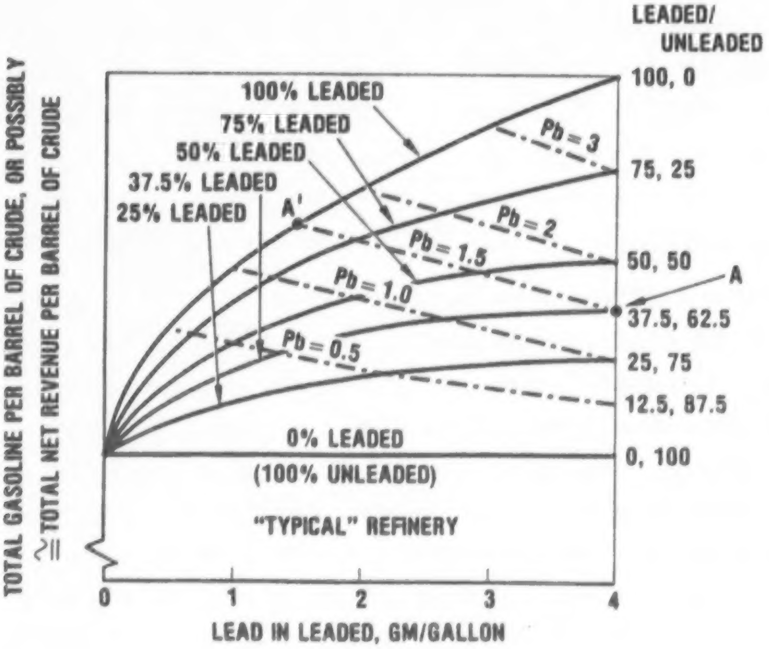

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Figure 1c

FIGURE 1. ILLUSTRATIONS OF PLAUSIBLE RELATIONSHIPS IN YIELD AND REVENUE OF REFINERIES PRODUCING BOTH LEADED AND UNLEADED GASOLINE UNDER SHORT SUPPLY CONSTRAINTS

gasoline, towards the point labeled A', where he produces 100 percent leaded gasoline of 1.5 gm/gallon. The refiner would undoubtedly not consider it feasible to move over this full range of course, as many constraints exist, but the pressures to move to more leaded and less unleaded, while meeting a pool average constraint, may well be as indicated.

The above treatment is clearly speculative and simplistic, but it does illustrate the more important point, the one made by President Carter (Ref. 22), that increases in lead in leaded gasoline can increase total and unleaded gasoline supplies. This approach involves certain penalties, as also alluded to by President Carter. Increases in lead will cause airborne lead to increase, with a corresponding increase in adverse health effects; in addition, any misfueling which occurs, will, with greater lead content, presumably do more damage to a catalyst pack, than would a lower lead content fuel, and a corresponding increase in emissions could be expected. These issues deserve more detailed examination, but lack of data prevents their further consideration here.

CONCLUDING COMMENTS

Shortages of unleaded gasoline in a crude-short situation involve potential air quality problems for which there are no ideal solutions. Among the alternatives considered here (which have excluded pure economic incentivization) use of MMT in unleaded gasoline and increased use of lead in leaded gasoline appear to be the only alternatives open, and each must be justified in terms of reducing alternative potential evils. Steps have already been taken to utilize these options. Over a the longer term, the fraction of unleaded gasoline must be increased if catalyst deactivation is to be avoided. New regulatory approaches may be needed.

Also, over the longer term, maximum utilization of crude resources must be effected. This may once again call for difficult tradeoffs, e.g., in more SO_2 emissions from coal-fired power plants to avoid increased bydrocarbon emissions from automobiles. These alternatives need further study.

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INTERACTION OF MISFUELING DUE TO PRICE DIFFERENTIAL AND TO SHORTAGE

Douglas C. Dacy

In expectation of a tight gasoline supply situation this summer,[1] a number of solutions to the misfueling problem have been suggested. One solution that has attracted some attention is that of mandating at the gasoline pump a maximum price differential between leaded and unleaded gasoline. This proposal is based on an assumption that the principal motive behind misfueling behavior is price differential. While the discussion in this paper will include this kind of short-run solution, it is not necessarily addressed to price differential solutions.

I. THE PROBLEM

For the purpose of analysis we shall consider the following three reasons for misfueling:

(1) Price differential
(2) Performance
(3) Shortage of unleaded gasoline.

The Environmental Impact Statement (EIS)[2] of the Department of Energy (January 1979) as well as other studies and newspaper articles have stressed the first two. Addition of the third greatly complicates the short-run solution to the fuel-switching, or "misfueling," problem.

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[1] This paper was written in May 1979.

[2] U.S. Department of Energy, *Environmental Impact Statement: Motor Gasoline Deregulation and The Gasoline Tilt*, January 1979.

Suppose that the gasoline market is in equilibrium in the sense that the supply and demand for both leaded and unleaded gasoline are in physical balance at prevailing prices. There is no shortage in either market. Suppose, also, that the supply of unleaded gasoline is fixed in the short-run by technical considerations or that it is very inelastic. Finally, we accept qualitatively the positive relationship between fuel switching and price differential that most analysts are convinced exists.

Given the above assumptions we can state simply the potential problem in short-run solutions. Policies designed to encourage reswitching (changing back from leaded to unleaded gasoline) will also tend to induce a shortage of unleaded gasoline assuring its unavailability at times and this condition will stimulate misfueling motivated by the created shortage. On the one hand, some motorists will reswitch under inducement of the short-run policy but, on the other hand, other motorists will switch to leaded gasoline because of the shortage created by the policy. Even if the reswitchers outnumber the new switchers the environmental situation in the intermediate-run will deteriorate. The reason is that the reswitchers will not greatly reduce air pollution because, presumably, their catalysts have already been poisoned whereas the new switchers will greatly increase emissions causing immediate environmental degradation and eventually poison their converters--thereby worsening air quality. In terms of inventory accounting, the stock of destroyed catalysts could grow as a result of any short-run program that does not take measures to prevent switching due to shortage.

II. FORMAL ANALYSIS

The discussion in this section is highly stylized. It is intended more to present some simple ideas rather than to draw empirical conclusions.

The relationship between the misfueling rate and price differential can be expressed as

$$M_{df} = a + DF^{\beta} . \tag{1}$$

M_{df} is an index of the misfueling rate due to price differential, DF, and β is the misfueling response factor. M_{df} lies within the range 0 to 100 and is to be interpreted as "percent of total catalytic-equipped automobiles that are misfueled." DF is measured in cents per gallon. Since the response to price differential usually is assumed to be increasing,[1] $\beta > 1$. One should note the dimensionality of Equation (1). It would be more consistent to measure the variables in the same dimension, e.g., percentages. They are not measured that way in this model because the basic data to which this expression is to be fitted are not measured that way. Because M_{df} and DF are not measured alike, β, strictly speaking, is not an "elasticity" in the usual economic interpretation; and it takes on the dimension required to transform cents per gallon into a percentage. The parameter, a, can be interpreted as the fuel switching rate due to actual or imagined performance difference and it has a scale 0 to 100. Thus, when DF = 0, M_{df} would be positive. There are, of course, many functional forms that could be used to define the M_{df} curve but the one given above is the simplest and can be made fairly consistent with the data by fixing the value of β at about 1.2.

Some argue that the principal reason for misfueling is performance. At a recent rulemaking hearing held by the Department of Energy (May 10-11), representatives of the oil companies claimed, almost unanimously, that the major motive behind misfueling was engine performance. The Sobotka study[2] also found that "perceived performance" was a cause of fuel switching. That study estimated that six percent would switch to leaded gasoline even if the price differential were zero.[3] This could be interpreted as the misfueling rate due to performance. In Equation (1) above the value of the parameter a represents misfueling due to performance.

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[1] EIS, pp. III-43-48 and Appendix B.

[2] *An Analysis of the Factors Leading to the Use of Leaded Gasoline in Automobiles Requiring Unleaded Gasoline*, Sobotka and Company, Inc. and Market Facts Incorporated, September 29, 1978, pp. 18-20.

[3] *Idem.*, p. 24.

The extent to which misfueling would take place in consequence of queues due to shortages is not known. However, reasonable guesses can be made about the general shape of the function. The limits can be stated. With no shortage there should be no misfueling due to shortage and with a total shortage there probably would be nearly complete misfueling. Some motorists might refuse to misfuel under any circumstances, particularly if they thought that the shortage were temporary. Nevertheless, we shall assume that with no availability of unleaded gasoline there would be total misfueling. In any event, this is not a critical assumption from a practical point of view because the misfueling curve due to shortage is likely to take on similar values in the probable range of shortage, say 0 to 10 percent. Accordingly, we can specify a very simple equation for misfueling (M_{su}) due to shortage of unleaded gasoline SU

$$m_{su} = su^{\alpha} . \tag{2}$$

The shortage of unleaded gasoline (su) must be interpreted as "ratio shortage," i.e., demand minus supply (at a given price) divided by supply. In this interpretation su can take on values in the range of 0 - 1, and Equation (2) satisfies the above requirements. However, this range of values is smaller by a factor of 100 than the range assumed for M in Equation (1). To make the values of m_{su} and M_{df} of the same order, we rewrite Equation (2) as

$$M_{su} = \frac{SU^{\alpha}}{10^{2(\alpha-1)}} . \tag{2'}$$

The capital letters in Equation (2') correspond to the transformed values of lower case letters in Equation (2).

We shall assume that $\alpha > 1$. This implies that the switching rate due to shortage is less than the percent shortage but as the shortage becomes more acute, motorists will be more and more easily persuaded to switch.

The total switching rate (index) is the sum of the switching rates due to all causes. Thus, in our limited analysis $M = M_{df} + M_{su}$ where M is the total misfueling rate. Thus,

$$M = a = DF^{\beta} + SU^{\alpha}/10^{2(\alpha-1)} \qquad (3)$$

A change in DF causes a change in M and that, in turn, will cause changes in the demand for both leaded and unleaded gasoline. Note, again, that "shortage" is defined as the percent difference between supply and demand at an existing price. If prices were to adjust instantaneously, strictly speaking there could be no shortages. But if prices are set by law or if they do not adjust immediately, shortages or surpluses could occur as a result of changes in demand assuming short-run supply is fixed. We assume that a change in the price differential will lead to demand change for unleaded gasoline with no immediate change in supply. Thus, a reduction in the price differential which stimulates reswitching will increase the demand and create a shortage of unleaded gasoline. If the motorists who reswitched to unleaded gasoline are similar (on the average) with respect to driving habits, types of automobiles, etc., to the motorists using unleaded gasoline, the shortage created by their reswitching will be equal to their previous misfueling rate. Thus,

$$SU = \Delta M_{df} = DF_0^{\beta} - DF_1^{\beta} , \qquad (4)$$

where SU is the induced shortage of unleaded gasoline and DF_0 and DF_1 are the differentials before and after the change.

For the sake of illustration, let $\beta = 1.2$, a = 6 percent and DF = 5¢. Given these values $M_{df} = 6 + 5^{1.2} = 12.9$ percent. If the price differential were reduced to 3¢, $\Delta M_{df} = -3.2$ percent and SU = 3.2 percent.

The total misfueling rate as a function of DF is obtained by substituting (4) into (3).

$$M = a + DF_1^{\beta} + (DF^{\beta} - DF_1^{\beta})^{\alpha}/10^{2(\alpha+1)} \quad . \qquad (5)$$

Once again for illustration let $\alpha = 1.1$ with values of the other parameters the same as above. Then

$$M = 6 + 3^{1.2} + (5^{1.2} - 3^{1.2})^{1.1}/10^{.2} = 12.0 \text{ percent.}$$

Misfueling would fall, in this illustration, by .9 percent because of the assumption that $\alpha > 1$. If $\alpha = 1$ the misfueling rate would be unchanged as a result of the change in the price differential and if $\alpha > 1$, the misfueling rate would rise. Thus, the value of α is critical in the determination of the misfueling rate when the price differential is unchanged.

III. ECONOMIC AND ENVIRONMENTAL CONSEQUENCE

Narrowly focusing on the price differential as the cause of misfueling can result in faulty forecasts of the misfueling if, indeed, the unavailability of unleaded gasoline is a factor in misfueling. At best, using the single variable model ($M = f(DF)$) would overstate the benefits due to narrowing the differential and, at worst, it could produce a forecast with the wrong sign. It could make the problem worse.

Taking the analysis one step further it becomes apparent that misfueling is the wrong variable to focus on if economic welfare and environmental improvement are primary concerns. From the point of view of environmentalists it would be better to focus on destroyed catalysts as a proxy measure of air pollution. In terms of economic welfare, at the least, one must consider the cost of the queueing that would occur in the event of a shortage of unleaded gasoline.

For neatness our analysis separates misfueling into two groups: those who misfuel because of price differential and those who misfuel due to shortage. This distinction probably does not exist in the real world but at relatively low misfueling rates, it does little harm to analyze the problem in this way. If we assume that all of the price differentially-induced misfuelers have already poisoned their converters (the extreme assumption) then bringing them back into the unleaded market can have no beneficial consequences from either an environmental or economic point of view. We shall develop this theme in two hypothetical "case studies."

IV. ILLUSTRATIONS

Following are two hypothetical cases to illustrate the points made above.

Case A: In this case we assume these values:

Price differential before change, DF_0 = 5 ¢
Price differential after change, DF_1 = 0 ¢
Misfueling rate due to performance, a = 6 percent
Response to change in price differential, β = 1.2
Response to shortage, α = 1.1.

We also assume that the market for unleaded gasoline is in balance and there are no constraints on producing leaded gasoline. The essential feature of this case is that $\alpha > 1$. Given these assumptions the current misfueling rate would be 12.9 percent (calculated from Equation (3)), of which 6.9 percent would be due to price differential. Suppose that 60 percent of these are regular misfuelers so that 7.74 percent of the catalysts in the unleaded car fleet have been destroyed. For a fleet of 40,000,000 cars the number of destroyed catalyst would be 3,096,000. (The percentage of misfuelers with destroyed catalysts is not important to the analysis.)

Now, suppose the price differential were reduced to 0¢, including complete reswitching by those misfuelers who are economically motivated. 6.9 percent reswitching would cause a shortage of unleaded gasoline by that percentage. As a result queues would form and this would encourage 5.3 percent misfueling due to shortage. An additional 1,956,000 catalysts would be subject to poisoning [.053 x (40,000,000 - 3,096,000)]. If 60 percent of them were eventually destroyed this would add 1,174,000 to the existing stock of poisoned catalysts, making the total 4,270,000. Thus, lowering the price differential to 0¢ would lead to a lowering in the misfueling rate from 12.9 percent to 11.3 percent but the number of potentially destroyed catalysts would rise by 40 percent. Air quality would be worse. These calculations are shown in Table 1.

But that is not the only cost. The final shortage of unleaded gasoline in this static model would be 1.3 percent (6.9 percent reswitchers minus 5.3 percent new shortage-motivated switchers). This shortage would mean that about 520,000 motorists would not be able to buy unleaded gasoline at each period of the gasoline "fill-up cycle" or that all unleaded motorists would have to wait in line to get less gasoline than they desire. The waiting time or "outage" inconvenience are clearly welfare costs and could be calculated in principle. Thus, from a strictly private point of view, economic welfare would be reduced to add to the reduction in social welfare due to the increase in pollution.

Case B. For this case we assume the same values as in Case A except that the coefficient of response to shortage (α) is taken to be 0.9. The essence of Case B is that $\alpha < 1$. This case is presented to bring out the point that the misfueling process is self-limiting. According to these unconstrained equations a lowering of the price differential to 0¢ would induce reswitching of 6.9 percent (as in Case A) but new misfueling due to shortage would occur at the rate of 9.0 percent ($(5^{1.2})^{.9}/10^{-.2} = 9.0$). This, of course, would not happen for that amount of switching would imply a *surplus* of unleaded gasoline. In this condition there would be no need for more than 6.9 percent to

Table 1. MISFUELING RATE AND CATALYSTS DESTROYED FOR SELECTED VALUES OF α WHEN $\beta = 1.2$

	Misfueling Rate, Percent			Catalysts Destroyed[a]		
Value of α	5¢ Differential[b]	0¢ Differential[c]		5¢ Differential[b]	0¢ Differential[c]	
		(Unconstrained)	Constrained		(Unconstrained)	Constrained
0.9	12.9	(15.0)	12.9	3,096,000	(5,089,000)	4,624,000
1.0	12.9	(12.9)	12.9	3,096,000	(4,624,000)	4,624,000
1.1	12.9	(11.3)	11.3	3,096,000	(4,270,000	4,270,000

[a] Percent of catalysts destroyed is assumed to be 60 percent of the misfueling rate. With no shortage of gasoline at the 5¢ differential, catalysts destroyed = .6 x .129 x 40,000,000 (catalytic fleet) = 3,096,000.

[b] Assume no shortage of unleaded gasoline.

[c] At 0¢ price differential a shortage of unleaded gasoline is assumed. The unconstrained misfueling rate is calculated as $M = a + DF_1^{1.2} + (DF_0^{1.2} - DF_1^{1.2})^{\alpha}/10^{2(\alpha-1)}$. The constrained misfueling rate is calculated with the same formula except that it is not allowed to exceed the misfueling rate with zero shortage, i.e., when price differential is 5¢. Catalysts destroyed at 0¢ differential is calculated as,

$$CD(0¢) = CD(0¢) + .6\ (\text{Induced Shortage})(\text{Catalytic Fleet} - \text{Previously Destroyed Catalysts}).$$

The induced shortage is, $IS = M(0¢)/100 - .6$, where M is the total misfueling rate read from the table.

misfuel on account of shortage because when that amount of switching occurred, the unleaded gasoline market would be in equilibrium again and no more misfueling on account of shortage would occur.

Using the assumptions in Case A an additional 1,528,000 catalysts would be poisoned. Environmental quality would be worse than in Case A. However, the misfueling rate would remain at 12.9 percent. There would be no queueing in this hypothetical situation.

V. FURTHER CONSIDERATIONS

The two cases discussed demonstrate the need for research on how a shortage of unleaded gasoline will affect motorists' misfueling behavior. More specifically, how will they respond to one or a sequence of frustrations at the pumps for unleaded gasoline? What are their "breaking points"? A motorist who finds no unleaded gasoline may not misfuel on that first frustration. What will he do if he is frustrated on two consecutive attempts? If he is finally successful, will he then forget about the previous failures or remember them with reduced intensity? We need a better idea about what to expect in misfueling behavior in periods of shortages.

Shortages can occur for many reasons. In this paper shortages were assumed to be created by reducing the price differential between leaded and unleaded gasoline. In the intermediate future it is most likely that shortages will occur in the market for unleaded gasoline because demand is growing by past government design whereas growth of supply has been inhibited by another set of regulations. We think that shortages will be the major cause of misfueling in the future. In any event a value of α in excess of one will always be self-limiting. This is so because the percent misfueling due to shortage cannot exceed the percent shortage in the equilibrium solution regardless of the reason for the shortage.

TAXATION AND SUBSIDIZATION POLICIES AS MEANS OF REDUCING MISFUELING IN TIMES OF GASOLINE SHORTAGE

Robert E. Kuenne

One of the frequent policy suggestions for the reduction of misfueling--on the tacit or explicit assumption that a major motivation for it is the price differential between unleaded and leaded gasoline--is the reduction of that differential by government action. It is proposed that a tax on leaded gasoline be imposed or a subsidy on unleaded gasoline be granted to its producer, jobber or retailer, or that both actions be taken together.

We shall show that the impacts of such policies upon misfueling are sensitive to whether shortages of the two types of fuel exist. In periods of shortage of unleaded, leaded or both types of gasoline, we feel these policies will actually be counterproductive because the stock of ruined catalytic converters will rise while they are in effect. Only when such shortages are nonexistent, we feel, will these policies have a potential to reduce the misfueling rate, and then only to the extent an important motivation for the improper action is the magnitude of the pre-policy price differential.

We turn in this paper to the task of demonstrating the validity of these propositions. In Section I we investigate the policies under conditions of sufficiency of supply. We then turn in Section II to the analysis of the proposals when the markets for one or both types of gasoline are experiencing excess demand. Finally, Section III contains a brief summary and conclusion.

1. THE MARKETS IN EQUILIBRIUM

Consider the markets for leaded and unleaded gasoline depicted in Figures 1a and 1b respectively. Each has achieved an equilibrium price P_L^1 and P_U^1 in the initial pre-policy state. Demand and supply in each market are equal.

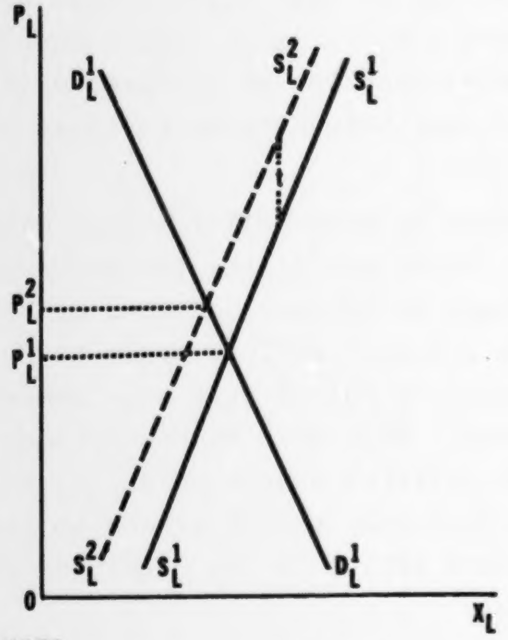

Figure 1a. The Leaded Market

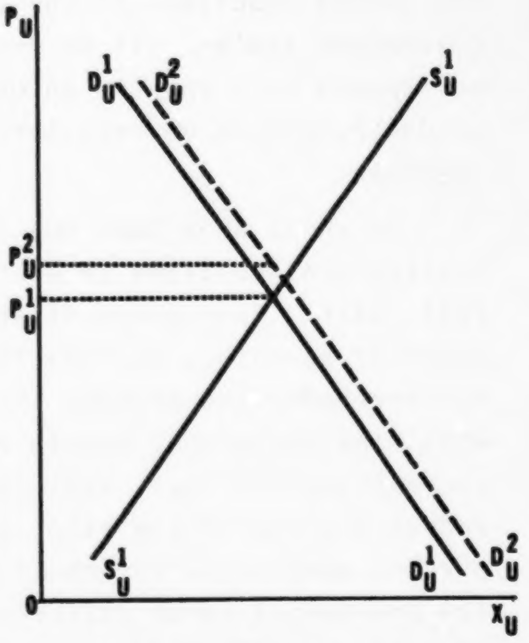

Figure 1b. The Unleaded Market

1.1 AN EXCISE TAX ON LEADED GASOLINE

As Policy Option 1 let us impose an excise tax t upon the leaded market (via retailer, wholesaler, or refiner) which effectively shifts the supply curve of leaded to $S_L^2 S_L^2$ and raises its price to P_L^2. The reduction in the amount of leaded gasoline demanded will be made up of two components in terms of motivation: (1) the higher price of leaded will reduce the amount demanded by proper fuelers and (2) the higher price of leaded will lead some misfuelers to reenter the unleaded market. The latter group will shift the demand for unleaded to $D_U^2D_U^2$, raising the price slightly and reducing the effect of the policy on the differential somewhat. If the demand for gasoline is non-price inelastic, the net effect is to increase the use of unleaded because the decrease in demand attributed to the higher price for unleaded will probably be outweighed by the increase in demand attributed to return of errant misfuelers.

Our language concerning the "return" of misfuelers to proper fueling or the forestalling of those who might misfuel in the absence of policy needs clarification. In the short-run we will indeed have movement from the unleaded to the leaded market and vice versa. This movement implies that the short-run payoff to the tax policy is somewhat diminished because the damage that has been inflicted by multiple misfuelings upon catalysts reentering the unleaded market is irreversible. Only a portion of those catalysts will therefore be saved further damage, depending upon how long the prior price differential has ruled and the state of public information about the wisdom of a move back to unleaded.

In the long-run our interpretation of these changes in demand is more optimistic. We must view the "reduction" in improper use of leaded gasoline as a *prevention* of misfueling that would have occurred in the absence of the policy and the "return" of misfuelers as a retention of those who would have continued to misfuel in the absence of the policy. The impacts of the reduced differential upon misfueling are then wholly beneficial. The question of efficacy turns in the long-run upon the empirical question of the strength of the price differential in determining misfueling rates.

Against the short- or long-term benefits must be weighed economic and political costs. In standard economic welfare terms, the tax inflicts a net social cost upon the society so long as social costs are adequately measured in the supply curve. We have reproduced the graphical depiction of the leaded gasoline market (Figure 1a) in Figure 2 for convenience. The excise tax, t, imposes a "deadweight loss" upon consumers and firms of ABC. The rise in price and attendant reduction in demand reduces consumers' utility in dollar terms by $BCX_L^1X_L^2$, whereas the social costs of producing the reduced output of OX_L^2 fall only $ACX_L^1X_L^2$ below those of the initial output OX_L^1. The difference between lost social benefits and recaptured resources is ABC, which is not recoverable. Firms lose AEC of the total and consumers BEC. Moreover, this analysis assumes that government spending of the tax revenues $P_L^1P_L^2BA$ are as equally rewarding in social utility as the uses that were formerly made of it in private hands. If government is adjudged

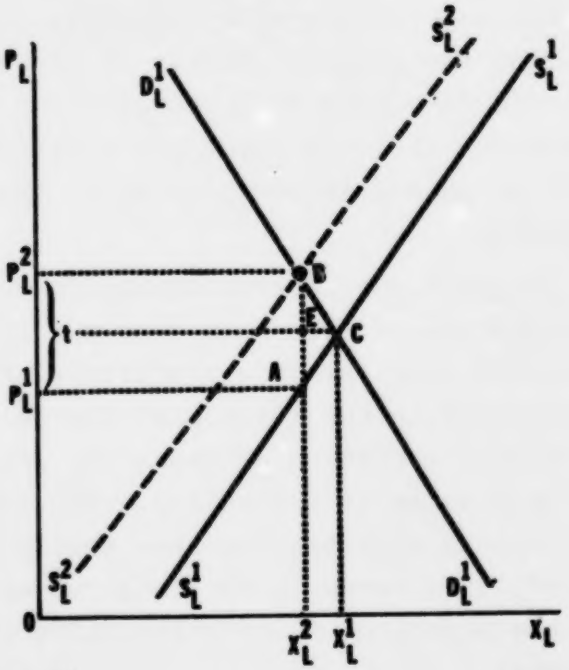

Figure 2. WELFARE IMPLICATIONS IN THE LEADED MARKET

to spend the tax receipts wastefully, the welfare costs of the tax are even higher. However, if the social gain due to reduced pollution exceeded ABC, the tax would result in a net social gain.

Less objectively, the policy may be judged to have undesirable equity effects. If users of leaded gasoline--that is, the owners of older automobiles--are assumed to be poorer than users of unleaded, an excise tax of this type places the burden of preventing or correcting misfueling upon poorer members of the community. The political costs of such a policy could be signi significant.

1.2 A SUBSIDY ON UNLEADED GASOLINE

Alternatively, suppose Policy Option 2 were a subsidy s per gallon of gasoline to be given to refiner, wholesale jobber, or retailer. In Figure 3 we begin with the initial equilibrium of Figure 1 and now assume, in Figure 3b, that the subsidy s is effected.

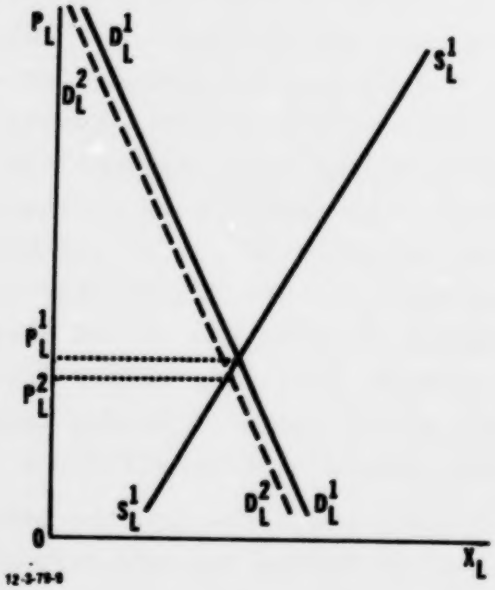

Figure 3a. THE LEADED MARKET

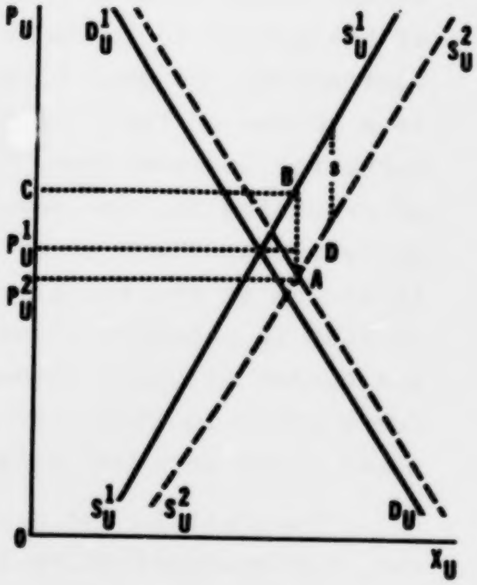

Figure 3b. THE UNLEADED MARKET

The price of unleaded gasoline falls initially by less than subsidy s because of the offsetting impact of an increase in the amount demanded. Reduction in the price differential between unleaded and leaded leads some misfuelers in the leaded market in the short-run to return to the unleaded market, shifting $D^1_U D^1_U$ to $D^2_U D^2_U$. Final price of unleaded is P^2_U with total government subsidy payments of $P^2_U ABC$, of which $P^2_U ADP^1_U$ reaches consumers as effective price relief.

In the same sense as that discussed above for Policy Option 1, only a fraction of the reformed misfuelers will be saving catalysts by returning to the unleaded market in the short-run. In the long-run, once more, this qualification to the results of the policy disappears because the policy increasingly will act preventatively rather than restoratively.

Several economic objections can be raised concerning the costs of these benefits in the short- and long-run. One is the extent of the effective price reduction purchased by potentially large subsidy payments. A second is that the net effect of the policy is to boost overall gasoline consumption. This contradicts the goal of reducing the nation's dependence on oil as a source of fuel. A third is that if the original supply curve for unleaded gas, $S^1_U S^1_U$, reflects the true marginal cost of producing it, the subsidy permits the consumer to purchase at less than the true cost thereby encouraging him to purchase in excess of the socially optimal amount. The fourth objection is that it subsidizes the consumption of gasoline on the part of the owners of newer automobiles without providing relief (except for a small indirect price reduction) to users of leaded gasoline, whose older cars may reflect their owners' lesser affluence.

Thus, within the contexts of both the long- and the short-run, the economic objections to Policy Option Two are stronger than those against Policy Option One.

The political objections may also be more strident because, in addition to the protests against favoring relatively affluent motorists, major segments of the public will react negatively to use of consumer taxes to pay subsidies to firms in the "suspect" oil industry.

1.3 A COMBINATION OF TAX AND SUBSIDY

Policy Option 3 is a simultaneous application of Policy Options 1 and 2: some portion, at least, of the subsidy on unleaded gasoline is "paid" from taxes upon leaded. The price differential is narrowed from both directions with less intense application of either option applied separately. The joint impact should simply be the sum of the respective impacts of Policy Options 1 and 2; all of the short- and long-run aspects of those options are applicable to their combination.

Taken singly or in combination, the tax-subsidy options share the characteristic of being indirect approaches to the reduction of misfueling and of acting upon a motive of uncertain strength. We find this disadvantage an objection to their usage.

The joint tax-subsidy policy seems to subsidize the producer and consumer of unleaded gasoline at the expense of the buyer of leaded gasoline (rather than at the expense of the general taxpayer). Unless tax and subsidy policies are tied directly in this fashion, this criticism is incorrect; but it (the criticism) could prove to be quite painful for those involved in the administration of the program.

2. EXCESS DEMAND IN ONE OR BOTH MARKETS

In this section we shall consider the short-run cases where either 1) the leaded market is in equilibrium and the unleaded market is experiencing excess demand, or 2) both markets are experiencing shortages at fixed prices. We shall omit consideration of the case where the unleaded market is in equilibrium and the leaded is experiencing excess demand as uninteresting in the context of concern about misfueling.

2.1 EXCESS DEMAND IN THE UNLEADED MARKET ONLY

2.1.1 An Excise Tax on Leaded Gasoline

In Figure 4 we depict an initial position in which the leaded gasoline market has attained an equilibrium but there exists a regulated fixed price for unleaded gasoline beneath the equilibrium price, which leads to an excess demand. In Figure 4b the amount AB is the excess of desired consumption over supply--the "excess demand" or shortage of unleaded gasoline.

Let us impose Policy Option 1--an excise tax, t, on leaded gasoline. On Figure 4a, therefore, the supply-curve shifts up by t to $S_L^2 S_L^2$. As in Section I this leads some misfuelers to reform, and to a resultant shift in the unleaded market demand function on Figure 4b rightward to $D_U^2 D_U^2$. However, because supply is not elastic, this movement merely enhances the excess demand already existing by the amount BC. Moreover, to the extent some reformed misfuelers whose catalysts are already ruined crowd out present unleaded users, and these latter now enter the leaded market to misfuel ($D_L^1 D_L^1$ shifts on Figure 4a to $D_L^2 D_L^2$), a net *increase* in the stock of ruined catalysts will result. The basic

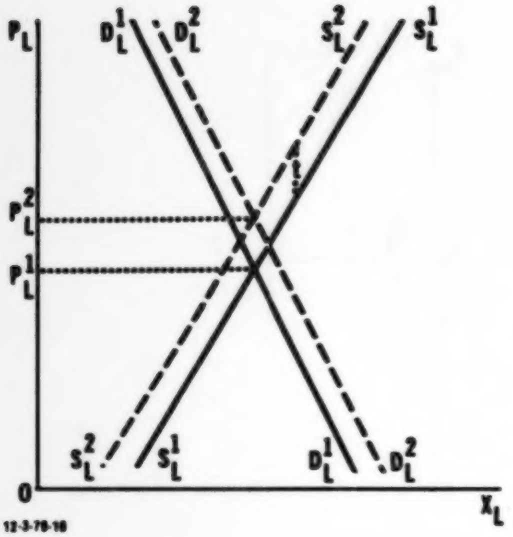

Figure 4a. The Leaded Market

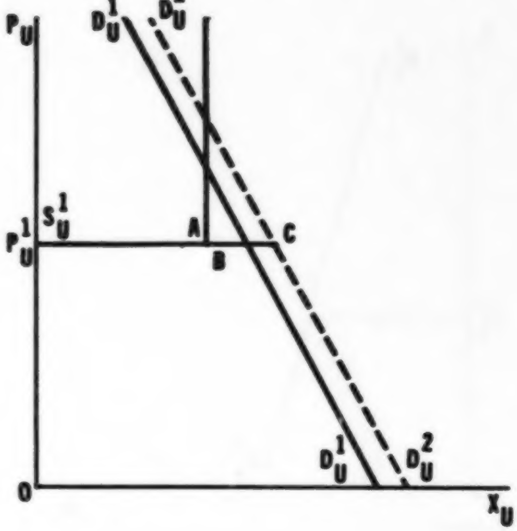

Figure 4b. The Unleaded Market

"asymmetry effect" results from the inability of some fraction of the reformed misfuelers' catalysts to benefit from movement to the unleaded market.

Hence, in periods of shortage in the unleaded market, a tax on leaded gasoline will worsen the consequences of the unleaded shortage on the stock of converters, not benefit it. Moreover, consumer dissatisfaction will rise because shortages in the unleaded gasoline market will intensify. The redistributive objections to, and the political implications of, this policy as discussed in Section I are applicable in this instance as well.

2.1.2 A Subsidy on Unleaded Gasoline

Policy Option 2 is depicted on Figures 5a and 5b with the placing of a subsidy, s, on the unleaded product. The immediate result in the unleaded market, of course, is to raise excess

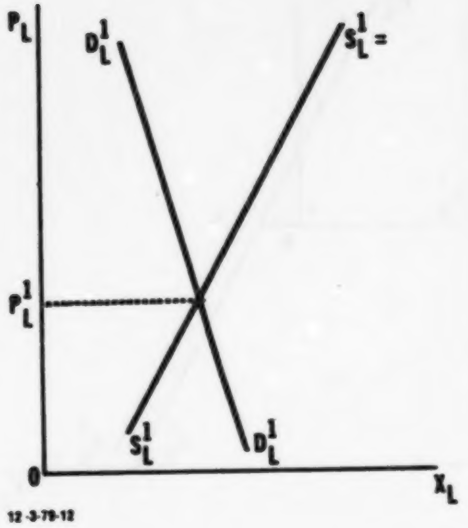

Figure 5a. The Leaded Market

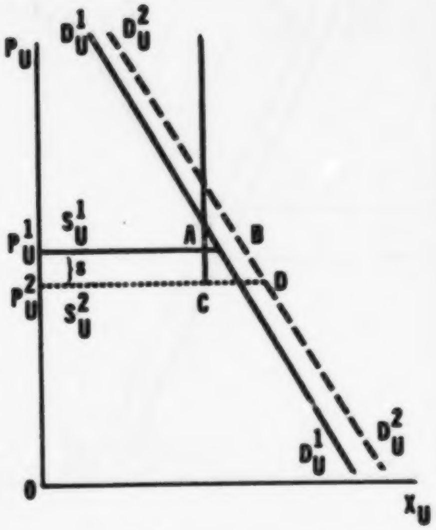

Figure 5b. The Unleaded Market

demand above AB on Figure 5b, increasing the frustration levels. This is intensified by a return of reformed misfuelers from the leaded market, as depicted in the shift of $D_U^1D_U^1$ to $D_U^2D_U^2$, yielding an enhanced excess demand of CD. Some of these consumers will enter the leaded market for the first time and misfuel. We assume in Figure 5a that $D_L^1D_L^1$ remains in about the same position after both adjustments--the shift from leaded to unleaded because of price differential reductions and the opposite flow of unleaded users to the leaded market.

While all of the objections raised to Policy Option Two when both markets were in equilibrium still hold, we will not repeat them; however, to them we must add that shortages in the unleaded market intensify, and that the stock of catalytic converters is degraded further. Both points intensify our objections to this option.

2.1.3 A Combination of Tax and Subsidy

In these circumstances the combination of Policy Options One and Two results in effects that are additive. However, despite the imposition of a tax in the leaded market, frustration levels will increase in the unleaded market. Hence, to the economic costs of the tax on leaded must be added the feeling that the costs are borne with the "effect" only of worsening the shortages of unleaded gasoline.

2.2. EXCESS DEMAND IN BOTH MARKETS

2.2.1 An Excise Tax on Leaded Gasoline

When the leaded gasoline market is in disequilibrium because of a regulated price too low to eliminate excess demand, all of the prior objections to this policy option remain valid and are augmented by several more. In Figure 6 we indicate that excess demand before the tax imposition implies that frustration of proper users of leaded gasoline will enhance the excess demand in the unleaded market. Hence the asymmetrical effect of switches between markets on the degradation of catalytic converters will operate more strongly than in Section 2.1.1. The excise tax will reduce the excess demand from AB to CD in Figure 6, it is true, and to the extent some of the reduction represents proper fuelers or misfuelers reducing their demand for gasoline some good in accomplishing *other* policy ends has been achieved. But to the extent part of the reduction consists of a new departure of owners of ruined catalysts or proper leaded gasoline users for the unleaded market, shifting the demand curve for it even farther right than in Section 2.1.1, because of the new component of proper leaded users, the post-tax situation is worse than the pre-tax by more than was true in Section 2.1.1.

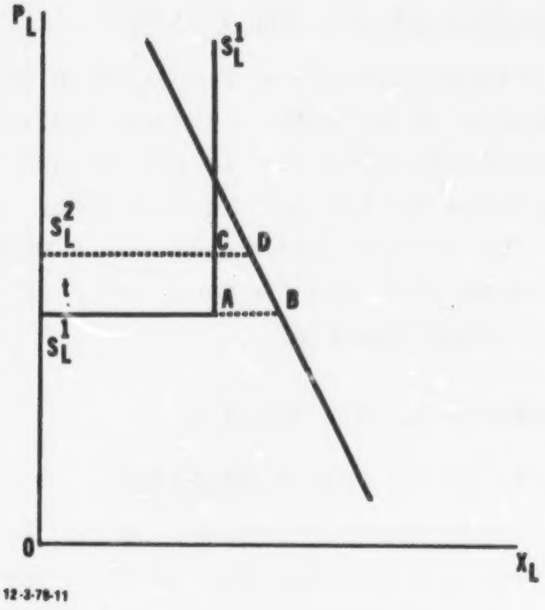

Figure 6. THE LEADED MARKET

2.2.2 A Subsidy on Unleaded Gasoline

The major difference that results from a subsidy on unleaded gasoline in conditions of excess demand in both markets is that the flow of reformed misfuelers to the unleaded market from the leaded market will be enhanced by proper leaded gasoline users who are frustrated in their search for leaded and find unleaded even more attractive than before the subsidy. We should expect, therefore, a stronger asymmetry effect on the degradation of the stock of converters. Moreover, frustration in both markets may make more intense the political criticism of increased frustration in the leaded market.

2.2.3 A Combination of Tax and Subsidy

Our conclusions concerning the economic and political effects of simultaneous use of both Policy Options One and Two are the same as those of Section 2.1.3.

3. CONCLUSION

In the longer run when leaded and unleaded gasoline markets are in equilibrium, either at fixed maximum prices or at completely unregulated prices, these two policies will have some beneficial effect in preventing misfueling and the degradation of the stock of catalytic converters. Even in these conditions, however, the policies have some economic and political drawbacks, involving taxes and subsidies that skew prices from marginal social costs and that raise perverse redistributive questions. Given the as yet unproved strength of the price differential as a motivation for misfuelers, these disadvantages may well outweigh the improvements the policies effect.

When frustrated excess demand exists in the unleaded market alone or in both markets, we can find very little to support these policies. They act singly or in concert to increase meaningful (i.e., net catalyst destroying) misfueling and thereby exacerbate the problem of a degraded converter stock. They raise the same redistributive questions as they do in the long run and tend to worsen frustration in one or both markets. Politically, therefore, their costs should be expected to be high. We find little in either the economic or political realm that recommends these policies in periods of generalized or unleaded gasoline shortage.

INSPECTION AND MAINTENANCE PROGRAMS AS A MEANS TO REDUCE THE INCIDENCE OF MISFUELING

Jeffrey A. Magnin

I. RATIONALE FOR INSPECTION AND MAINTENANCE (IM) PROGRAMS WITH RESPECT TO THE REDUCTION OF MISFUELING

The general rationale for IM programs is that they are an effective means to reduce emissions from vehicles. With respect particularly to the practice of misfueling, their purpose would be to identify, and to cause to have repaired, all vehicles with with catalysts rendered inoperable by the introduction of leaded fuel. This policy differs significantly from most others being considered. Since any one of several motives may account for misfueling, any policy which has as its goal the removal of a motive (such as a mandated price differential) is inherently inefficient: it will not discourage those whose motives for misfueling are different. The efficiency of an IM program is independent of guessing correctly the motives of the misfueler.

In addition, the policy is relatively equitable. If a mandated price differential were imposed, the costs would not be borne by misfuelers, but would likely be divided among refiners, retailers, and motorists properly using leaded gasoline. In contrast, the costs of compliance with an IM program--in this instance, replacing a "poisoned" catalyst--would be borne solely by that person whose decision it was to misfuel. Inspection and maintenance programs, then, can be an effective means to prevent degradation in air quality attributable to the practice of misfueling.

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II. TECHNICAL FEASIBILITY

There exist three fundamental requirements for any effective IM program: that all vehicles receive periodic inspections; that all failed vehicles be reinspected; and that personnel and equipment be subject to quality control measures to ensure reliability and accuracy. Beyond these minimum program requirements, the emissions-reduction potential of any particular IM program is dependent upon the program/technical options chosen by the state. An earlier study has cited six areas of choice,[1] but the most critical in determining the effectiveness of IM programs is the "cutpoints"--"that level of tailpipe emissions set, respectively, for HC and CO which distinguish between those vehicles requiring emissions-related repair work and those that do not."[2] By influencing the percentage of the vehicle population which fails, cutpoints help establish the rigor of the program. For purposes of political viability as well as public acceptance, however, they are set to yield tolerable failure rates--not optimal emissions levels. (An auto fails the inspection if it exceeds either cutpoint.) Importantly, while different cutpoints may be established for different groups of vehicles, they are chosen to identify all vehicles which violate emissions standards by a specified amount, regardless of the cause.

As a result of this perspective, the equipment required by current testing procedures cannot diagnose precisely which component of the engine is working improperly. Instead, it registers emissions levels for the pollutants HC and CO, and by the severity and mix of emissions violations can lead inspectors to the probable cause of violations. However, several diagnostic errors can occur. Certain maladjustments of engines and emissions-control systems can cause emissions to increase more at idle or test speeds than at driving speeds--thereby causing automobiles in compliance under normal conditions to fail inspection tests. Conversely, other maladjustments do not cause emissions to rise at idle speeds as much as at driving speeds. Consequently, this group of automobiles may pass inspection tests while in fact they violate emissions standards. This error can occur in the case of wholly or partially inoperable catalysts. Moreover, since catalysts are limited in their capacity to cleanse emissions, maladjustments of other vehicle components, which increase volumes of emissions, can cause the catalyst to appear damaged. Together these errors contribute to misdiagnosis of the condition of catalysts. Yet, because no other source of emissions violations registers similarly on current diagnostic equipment, trained inspectors should in most cases be able to identify an inoperable catalyst by its imprint.

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[1] US, EPA, Information Document on Automobile Emissions Inspection and Maintenance (EPA-400/2-78-001), February 1978.

[2] 40 CFR Part 51, Appendix N--"Emissions Reductions Achievable Through Inspection and Maintenance of Light-Duty Vehicles, Motorcycles, and Light and Heavy Duty Trucks," 19 April 1977, p. 22178.

IM programs may in the future become still more effective by the inclusion of a test developed specifically to identify poisoned catalysts. Several alternate testing procedures are now being assessed at EPA laboratories in Ann Arbor, Michigan, but none has satisfied the requirement that it be short, nor is the requisite diagnostic equipment commercially available. Notwithstanding the above, however, mandatory IM programs can be a technically-feasible solution to the problem of misfueling.

III. ECONOMIC FEASIBILITY

The feasibility of IM programs as a means to reduce the incidence of misfueling must in part be based upon the incremental costs to the program attributable directly to the inclusion of a test for poisoned catalysts. However, estimates of the costs are necessarily imprecise, for two reasons. The first is that no testing procedure nor diagnostic equipment has been approved by EPA for identifying poisoned catalysts specifically. Although the fact derives partially from non-economic considerations, such as the accuracy and the reliability of alternate procedures, its impact is to prohibit estimates of incremental costs.

The second reason is that, to the extent that there exists a relationship between program structure devised and costs incurred by the state, incremental costs necessarily remain indeterminate until program structure is specified.

Despite the above caveats, the inclusion of a test IM program for poisoned catalysts is likely to prove a cost-effective means of reducing the incidence of misfueling. IM programs emphasizing current testing procedures have already proven that they are economically feasible. Also, they are generally self-supporting: revenues generated by inspection fees cover annual expenses. The inclusion of a test, and the purchase of diagnostic equipment, designed specifically to identify poisoned catalysts, is unlikely to change this fact. Furthermore, the incremental costs should be more than offset by the benefits of identifying that cause of emissions violation which results in a degradation of air quality more severe than is caused by any other engine or exhaust system maladjustment. In light of our forecast of persistent shortage of unleaded gasoline, as well as of the greater sensitivity of catalysts introduced on model-year 1980 autos, this excess of benefits over costs is likely to increase.

Yet if costs to the states do not rise, costs to (some) motorists will. The proper criterion for measuring their costs is not cost of maintenance per se, but the cost of maintenance attributable to IM relative to the cost which would have been incurred without IM. By this criterion the net cost to most motorists is rather small; but since there exists no commercially available technology to reactivate an inoperable catalyst--in other words, replacement is the sole solution--the net cost of IM programs to misfuelers could be quite great.

However, there exists a provision in several current IM programs that exempts a vehicle owner from liability for compliance with emissions standards if repair costs exceed a specified limit--expressed as either an absolute amount or as a percentage of the vehicle's book value. These limits are high relative to average repair costs for violations other than misfueling, and thus exempt only a small percentage of those violators; but they are invariably lower (typically $75-$100) than the cost of replacing a catalytic converter. Consequently, the misfueler can pay the ceiling cost--in essence his fine for purposefully misfueling--and with his renewed license or inspection sticker continue to misfuel. When this provision is in effect, IM programs lose some effectiveness as a solution to the problem of misfueling.

IV. POLITICAL FEASIBILITY

Political feasibility is to some extent a moot question. Many states are required by the Clean Air Act Amendments of 1977 to implement mandatory IM programs in those urban areas where combined pollution from fixed and mobile sources exceeds EPA standards. Nonetheless, it remains an issue because the procedures and technologies to test for inoperable catalysts may more readily fit into one program structure than another, requiring that several extant programs be revised.[1] Furthermore, IM programs may have to be established in areas when otherwise no program would be needed. Finally, the nature of IM programs--with or without tests for poisoned catalysts--

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[1] For example, in decentralized programs, where private garages test all vehicles and retest failed vehicles, test results may vary widely and fraud may occur.

runs contrary to the public sentiment prevailing today for less, not more, governmental regulation.

In the event that all limits on repair costs are eliminated, replacing an inoperable catalyst is likely to be the most expensive repair a motorist is required to make. When testing is conducted by persons not working directly for state agencies, motorists may be unwilling to comply because of the perception that they are being required to do so by people without authority over them. This perception could arise with a centralized program generated by a company under contract to the state or in a decentralized program where testing is conducted at private garages. In either case the program structure--in particular, the division of authority and responsibility between state agencies and others--may have to be changed in order to promote public acceptance.

IM programs may encounter additional problems of public acceptance if for the purpose of identifying inoperable catalysts, they are established in areas which would otherwise not be required to implement them. The practice of misfueling is more widely dispersed than are those areas which fail to meet EPA standards for combined fixed and mobile-source pollution. Motorists in areas which currently conform may not welcome the imposition of periodic inspections to detect inefficient catalysts alone. Consequently, while it would be more effective from the standpoint of air quality to devise a consistent policy, there could be great resistance to IM programs within these areas.

Yet resistance arises even more broadly. IM programs constitute increased governmental control over the lives of citizens during a period when the majority preference is for less governmental regulation. IM programs are thus likely, if for no other reason, to be less politically acceptable than other proposed solutions to the problem of misfueling.

V. PROPOSALS

In order to strengthen IM programs as a means to reduce the incidence of misfueling, we make the following proposals:

1. to have states eliminate all limits on repair costs;
2. to incorporate into all existing and proposed legislation prohibitions against tampering with the pollution control system (prohibitions now vary from state to state); and
3. to tie inspections to the liscensing function of the state, so that vehicles not in compliance could not be driven legally.

AN ANALYSIS OF A FEDERAL LAW AGAINST MISFUELING BY MOTORISTS

J. Fred Giertz

I. INTRODUCTION

The major technological thrust in recent years to combat air pollution generated by automobiles (and thus meet Federally mandated omissions levels) has been the installation of catalytic converters in post-1975 automobiles. To maintain the effectiveness of the catalytic converters, automobiles must use unleaded gasoline almost exclusively, although these automobiles will perform effectively on leaded gasoline. Since leaded gasoline is cheaper and usually of higher octane (giving better performance characteristics) than unleaded gasoline, motorists have a certain incentive to substitute leaded for unleaded gasoline. This misfueling of automobiles thwarts the achievement of improved air quality in a very important way since a small number of misfuelings can render the catalytic converter ineffective.

Certain rules and regulations imposed by the government make misfueling inconvenient for a motorist who wishes to use leaded fuel. The gasoline tanks of automobiles with catalytic converters will not accept the hose nozzle of leaded gasoline pumps and there are severe penalties for service stations which engage in misfueling. However, it is fairly easy to modify the gasoline tank opening or to use a funnel to make misfueling possible. In addition, there is, at present, no penalty for the motorist who misfuels using self-service pumps. One suggested remedy to reduce the misfueling problem is to

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pass a Federal law which would make it a crime for motorists as well as service stations to misfuel. This strategy of making misfueling a criminal violation for the motorist is the subject of this analysis.

The effect of such a law on the consumers' decision to misfuel will be investigated first. Then the operation of the overall system will be analyzed to derive the optimal configuration of enforcement and penalties which achieve the environmental quality goal of the Federal government. The paper concludes with a discussion of policy implications as well as the data requirements to implement the program.

II. THE CONSUMER'S DECISION TO MISFUEL

The motorist's choice between leaded and unleaded gasoline should be expected to be based upon narrow considerations of private benefits versus private costs. It is unlikely that a large number of consumers will refrain from using leaded gasoline solely because of environmental considerations. This is not to say that motorists do not value clean air, but the free-rider problem creates a very severe disincentive for voluntary private sacrifice to improve the environment. The reduction in pollution by using unleaded gasoline by any one consumer is so small that it has a negligible impact on air quality. Therefore, an individual has little private incentive to pay a higher price for lead-free gasoline which gives inferior performance as compared to leaded gasoline.

This analysis will, therefore, concentrate on the private aspects of the consumer's decision to misfuel. Listed below is a summary of the private benefits and the costs of using leaded gasoline in autos equipped with catalytic converters:

BENEFITS

1. Lower cost per gallon.
2. Better performance characteristics and possibly better mileage because of higher octane.

3. Possibly less time to fuel and greater availability of leaded fuel if shortages exist.

COSTS

1. Difficult and inconvenient fueling--self-service pumps are needed and modification of gasoline tank opening is necessary.
2. Increased wear on exhaust system and increased need for tune-ups resulting from the use of leaded gasoline.
3. Personal ethical-environmental costs resulting from misfueling--motorists may feel guilty about negating the law and degrading the environment.
4. Potential punishment resulting from misfueling (applies only if misfueling is a crime).

Obviously, it would be expected that misfueling would occur when the benefits in the consumer's mind exceed the expected costs.

To formulate this choice problem more formally, assume a motorist in an automobile equipped with a catalytic converter will purchase a given quantity of gasoline in a particular period and must decide between leaded and non-leaded. Let I_n represent the consumer's income (both pecuniary and psychic), measured in dollars, from the exclusive use of unleaded gasoline while I_m represents the same person's income (not including any penalty costs) when misfueling is practiced exclusively. The difference between I_m and I_n represents the motorist's evaluation in monetary terms of the use of leaded gasoline over unleaded and reflects the benefits and costs discussed above.

If misfueling is not illegal for the motorist, the choice is very simple: use leaded gasoline if $I_m > I_n$ and use unleaded if $I_n > I_m$. Making misfueling a crime, however, introduces an additional element of uncertainty into the analysis since the cost of misfueling is increased by the possibility of a penalty being assessed being assessed against the offender.[1] In such a situation, the motorist is not sure of the actual income that will result with misfueling since it depends upon whether he is apprehended and convicted of the violation or not. This situation is analyzed below.

Confronted with the possibility of punishment for misfueling, a motorist is not forced to engage exclusively in using either leaded or unleaded gasoline. Let g_m represent the fraction of the motorist's overall gasoline usage which is leaded, $0 \leq g_m \leq 1$, and let p_a be the probability of apprehension if leaded gasoline is used exclusively during the period in question. The possible outcomes facing the consumer are given in the table at right where the values in the boxes represent the probability of occurrence of the various outcomes. This shows that the likelihood of punishment ($g_m p_a$) depends upon both the level of enforcement (p_a) and upon the extent to which the illegal activity is engaged in.

	Misfueling Practiced	**Unleaded Gasoline Used**
Consumer Arrested	**Arrest and Conviction** $g_m p_a$	**Arrest and No Conviction** $(1-g_m)p_a$
Consumer Not Arrested	**No Arrest** $g_m(1-p_a)$	**No Arrest** $(1-g_m)(1-p_a)$

In this situation the motorist's income is no longer certain. Income depends upon the fraction of leaded and unleaded gasoline which is used and whether or not the person is arrested and punished for misfueling. The consumer's income if he is not assessed the penalty is:

$$g_m I_m + (1-g_m)I_n \text{ and}$$

$$g_m I_m + (1-g_m)I_n - \text{Pen} ,$$

if a penalty of magnitude Pen (measured in dollars) is levied. These incomes will occur with the probability of $(1-p_a g_m)$ and $p_a g_m$ respectively, yielding the consumer's expected income of the following:

$$g_m I_m + (1-g_m)I_n - g_m p_a \text{Pen} .$$

From this equation, it can be seen that if the consumer engages in no misfueling, i.e., $g_m = 0$, his income will be I_n with certainty since the probability of a penalty being levied is zero. If misfueling is practiced exclusively, $g_m = 1$, expected income will be $I_m - p_a Pen$.

If the consumer is interested only in maximizing expected income, he would choose g_m in such a way to achieve this goal. This would result in a corner solution where only leaded or only unleaded fuel would be used ($g_m = 0$ or $g_m = 1$) depending upon the values of I_m, I_n, p_a and Pen. This situation would not necessarily result if the consumer is not neutral with regard to risk. In this analysis, the variance of income will be used as a measure of risk with:[2]

$$\text{Var}(I) = (1-g_m p_a)(g_m p_a)\text{Pen}^2 \ .$$

The consumer's utility is a function of both expected income and the variance of income such that:

$$U = U(E(I), \text{Var}(I)) \ .$$

The consumer must choose g_m, the fraction of leaded gasoline to use, to maximize U. This process yields the following condition (assuming a non-corner solution):

$$\frac{\partial U}{\partial g_m} = \frac{\partial U}{\partial E(I)} \frac{\partial E(I)}{\partial g_m} + \frac{\partial U}{\partial \, \text{Var}(I)} \frac{\partial \text{Var}(I)}{\partial g_m}$$

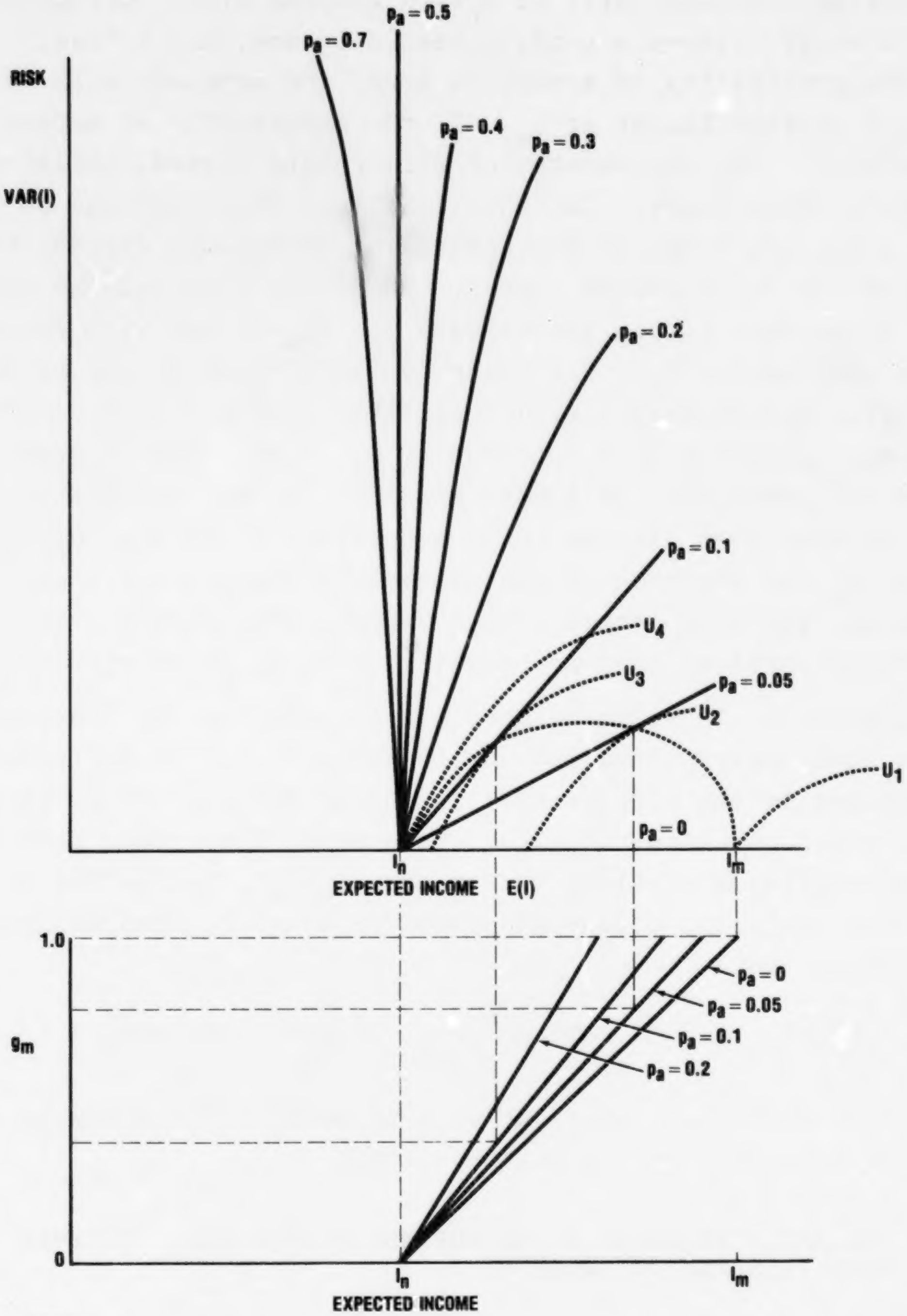
$$= \frac{\partial U}{\partial E(I)} (I_m - I_n - p_a \text{Pen}) + \frac{\partial U}{\partial \, \text{Var}(I)} (\text{Pen}^2 p_a (1-2p_a g_m))$$

This can be interpreted in the following way for a risk averse consumer: the first term represents the gain in utility from a higher expected income resulting from an increase in the proportion of leaded gasoline used while the second term represents the decrease in utility because of greater risk. If an internal solution exists, the consumer will keep increasing g_m until the marginal utility of higher expected income from using leaded gasoline just equals the marginal disutility of the greater risk.

It can be seen from this analysis that a variety of factors aside from the individual's own preferences can affect the choice between leaded and unleaded gasoline. In particular, changes in the probability of arrest, p_a, through changing enforcement techniques and changes in the severity of the penalty affect both expected income and the degree of risk and thus, the consumer's choice of g_m. In addition, the differential between I_m and I_n caused by, among other things, the price and performance differential between leaded and unleaded gasoline and the conscience costs consumers may feel when they violate the law affect expected income and thus utility.

The consumer's maximization decision is portrayed geometrically in Figure 1 which illustrates the response to changes in the probability of arrest.[3] In the upper diagram, the various constraint lines (labelled p_a=0, p_a=.05, etc.) show the opportunity locus for given probabilities of arrest. For example, if the probability of arrest is zero, there would be no risk associated with the decision to misfuel and the constraint would extend from I_n to I_m along the horizontal axis with the consumer presumably maximizing utility at I_m by letting $g_m = 1$. Increasing the probability of arrest above zero has two effects. It decreases expected income and, in most ranges, increases the variance of income. This is shown by the rotation of the constraint line by varying g_m. The constraint resulting when $p_a = .5$ is vertical indicating that the expected income is constant for any choice of g_m since, in this case, the increase in the basic income from misfueling is exactly offset by the decrease in expected income from the increased expected value of the punishment. At some probability of arrest level, the constraint may be negatively sloped indicating that increasing the use of leaded gasoline both lowers expected income and increases the risk involved.

To determine the equilibrium position, it is necessary to introduce the consumer's indifference maps which, for the



$p_a = 0.5$
$p_a = 0.7$
RISK
$p_a = 0.4$
$p_a = 0.3$
VAR(I)
$p_a = 0.2$
$p_a = 0.1$
U_4
U_3
$p_a = 0.05$
U_2
U_1
$p_a = 0$
I_n
I_m
EXPECTED INCOME
E(I)
1.0
g_m
$p_a = 0$
$p_a = 0.05$
$p_a = 0.1$
$p_a = 0.2$
0
I_n
I_m
EXPECTED INCOME
8-15-79-1

risk-averse consumer, will be upward sloping since they portray the trade-off between a good, expected income, and a "bad," risk. When the probability of arrest is zero, the consumer will maximize his certain income at I_m. If the probability of arrest is increased to .05, the constraint will rotate upward, yielding a new equilibrium point. Internal solutions will continue to exist until the slope of the constraint everywhere exceeds the slope of the indifference curves. When this happens, the consumer will cease to use leaded gasoline ($g_m=0$) and will choose the certain income I_n. The locus of equilibrium points (similar to a price consumption curve) implicitly yields a demand curve for leaded gasoline as a function of p_a. The lower diagram allows the proportion of leaded gasoline for each equilibrium point in the upper diagram to be determined since the combination of p_a and expected income uniquely determine g_m. As p_a increases, the risk averse consumer would consistently reduce misfueling until at some probability level g_m would equal zero.

Similarly, it would be possible to show how the constraints change with regard to variations in the severity of the penalty and changes in the differential in income between using leaded and unleaded gasoline, (I_m-I_n). This would also yield demand curves relating misfueling to Pen and (I_m-I_n), respectively. From this analysis, a general demand relationship can be hypothesized such that

$$g_m = f(I_m-I_n,\ p_a,\ \text{Pen}) \text{ where } \frac{\partial g_m}{\partial(I_m-I_n)} > 0,\ \frac{\partial g_m}{\partial p_a} < 0, \text{ and } \frac{\partial g_m}{\partial\, \text{Pen}} < 0\ .$$

A function similar to this one will be used in the analysis of the overall system in the next section.

III. THE APPLICATION OF A LAW AGAINST MISFUELING: OPTIMAL PENALTIES AND ENFORCEMENT

While a law penalizing motorists for misfueling will clearly not eliminate the problem, it will, at least, give the government an additional weapon to control the extent of misfueling. The analysis in the preceding section suggests that both the severity of punishment and the probability of arrest and conviction will, among other factors, determine the extent of misfueling. In this section, the optimal levels of penalties and enforcement relating to misfueling will be derived. These values will minimize the combined costs of the net damage caused by misfueling plus the costs associated with the operation of the law enforcement system which administers the prohibition against misfueling.

First, it is necessary to modify the demand function for leaded gasoline (for automobiles equipped with catalytic converters) which was derived in the preceding section. The misfueling function is given by

$G_1 = f(b_m, p, Pen)$ where

G_1 represents the quantity of leaded gasoline used in misfueling; b_m is the net private benefit to the motorist (per unit of gasoline) of using leaded rather than unleaded gasoline; p is the probability of arrest and conviction (per unit of misfueling) and Pen is the penalty for arrest and conviction for misfueling. b_m is very similar to the difference between I_m and I_n discussed in Section II and reflects the benefits and costs listed on pages 154 and 155. It represents the fact that leaded fuel is cheaper and gives better performance than unleaded gasoline. If b_m were negative, there would be no misfueling problem.

The net private benefit of misfueling must be weighed against the environmental damage which it causes. The environmental damage (per unit of misfueling) is given by the term d_e. This represents the cost (per unit of leaded gasoline) to society of the pollution resulting from misfueling. The value of d_e is assumed constant, although it might be expected to change for major shifts in G_1. The net social damage from misfueling is given by:

$$\text{Net Social Damage} = (d_e - b_m)\, G_1 .$$

In this analysis, the benefits to the offender (lower cost, better performance, etc.) of misfueling to a certain extent, offset the damage to the environment. There has been some discussion in the literature as to whether the offender's gain should be counted in the analysis of the optimal response to crime.[4] For example, should the psychic income received by the perpetrator of a violent crime be weighed against the harm done to the victim? While this general question is unresolved, it does seem appropriate to include the benefit gained by the motorist in misfueling since this is hardly the equivalent of murder or assault. In fact, if the net private benefit to the motorist of misfueling exceeds the environmental damage, i.e., $b_m > d_e$, the prohibition against misfueling is not economically justified to begin with.

The goal of the government should not be merely to minimize the damage caused by misfueling, since the prevention of misfueling is a costly, resource using activity. These costs of prevention have to be considered in the determination of the optimal strategy. One obvious cost of prevention is the cost of enforcing the misfueling law (C_e). The level of enforcement activity, C_e, determines the probability of arrest and conviction which in turn affects the extent of misfueling. In addition to enforcement costs, there is the cost of imposing the penalty on the violators, C_p, the cost of punishment. This is the cost of maintaining courts, prisons, etc. In the case of fines (the likely penalty for misfueling), the cost of punishment is likely to be relatively modest as compared to the cost of incarceration. It should be noted that the amount of the fine itself is not counted as either a cost or a benefit in this analysis since it is a pure transfer. The cost of imposing and collecting fines, however, is included as a cost.

The goal of the government in regard to misfueling should be to minimize the overall cost of misfueling plus the cost of preventing misfueling:

$$\text{Total Cost} = \text{Net Social Damage} + \text{Cost of Enforcement} + \text{Cost of Punishment}$$
$$= (d_e - b_m)\, G_1 + C_e + C_p \,.$$

The policy variables available to the government are C_e, the amount of resources devoted to enforcement, and Pen, the severity of the punishment. Minimizing this function with respect to C_e and Pen give the following first order conditions:

$$\frac{TC}{C_e} = (d_e - b_m)\, \frac{\partial G_1}{\partial p}\, \frac{\partial p}{\partial C_e} + 1 + \frac{\partial C_p}{\partial C_e} = 0$$

$$\frac{TC}{Pen} = (d_e - b_m)\, \frac{\partial G_1}{\partial Pen} \quad \frac{\partial C_p}{\partial Pen} = 0 \,.$$

The first equation suggests that an extra dollar should be spent on enforcement as long as the damages abated from the expenditure on enforcement (the first term) exceeds that dollar of enforcement costs (the second term) plus the additional cost of administering the punishment resulting from greater enforcement (the third term). Likewise, the second equation suggests that penalties should be increased as long as the net environmental damage prevented exceeds the marginal cost of more severe penalties.[5] This analysis might seem to suggest the use of extremely severe fines with a rather low level of enforcement. This strategy, however, is probably not optimal in that there is a social cost associated with this sort of arbitrary enforcement situation that should be included in the cost of punishment relationship. Most citizens would likely feel that singling out a very small fraction of violators for extremely harsh punishment is unfair and undesirable.[6]

One problem connected with the imposition of a law against misfueling which has not yet been considered is the fact that enforcement measures accompanied by effective penalties may induce drivers who have previously engaged in misfueling to return to the use of unleaded gasoline. In such a case, the previous analysis would have to be modified to take into account the fact that the return to unleaded gasoline for such automobiles would have little if any environmental impact since the catalytic converters would no longer be functioning, yet it would entail a loss of performance plus an increase in the demand for unleaded gasoline which is already in short supply. The importance of this problem depends upon the fraction of automobiles with non-functioning catalytic converters. Unfortunately, there may not be any governmental policy which is subtle enough to distinguish between the two groups. If, however, the effectiveness of the catalytic converter is a function of age, the law might be made to apply only to autos of more recent vintage or enforcement might be directed primarily at more recent model automobiles.

One other important factor has not as yet been examined. This is the variation in the damage caused by pollution among the different regions in the country. Obviously, the damage caused by misfueling depends upon such things as geographic and climatic conditions, the density of population, travel patterns in each area and the existing pollution from other sources. Misfueling in a congested urban area may have very severe air quality effects while the same activity may cause negligible damage in a rural area. This would suggest that the optimal level of pollution abatement would vary considerably from region to region.

This problem can be dealt with using an approach similar to that in the earlier part of this section by establishing a misfueling function for each of the k areas of the country such that

$$G_1^i = f(b_m^i, p^i, Pen), \quad i = 1, 2, \ldots, k.$$

where the superscript i represents the particular district in question. Since the law against misfueling would be a Federal one, it is likely that the penalty would be the same for all areas. However, the probability of arrest and conviction could be varied from area to area by the strategic distribution of enforcement resources. In this case the total cost function to be minimized would become:

$$\text{Total Cost} = \sum_{i=1}^{k} (d_e^i - b_m^i) G_l^i + \sum_{i=1}^{k} C_e^i + \sum_{i=1}^{k} C_p^i .$$

Minimizing this function yields the following first order conditions:

$$\frac{\partial TC}{\partial C_e^i} = (d_e^i - b_m^i) \frac{\partial G_l^i}{\partial p^i} \frac{\partial p^i}{\partial C_e^i} + \frac{\partial C_p^i}{\partial C_e^i} = 0, \quad i = 1, 2, \ldots, k .$$

$$\frac{\partial TC}{\partial Pen} = \sum_{i=1}^{k} (d_e^i - b_m^i) \frac{\partial G_l^i}{\partial Pen} + \sum_{i=1}^{k} \frac{\partial C_p^i}{\partial Pen} = 0.$$

These conditions suggest that the optimal distribution of enforcement resources among the various regions depends upon the damage per unit in each area (d_e^i), the benefit from misfueling (b_m^i) and the relative effectiveness of enforcement measures. Other things equal, greater enforcement resources should be allocated to the areas with the highest marginal damage resulting from misfueling. These areas would presumably be urban areas with weather conditions and travel patterns which yield serious potential pollution problems. If enforcement expenditures are fixed, the preceding analysis could be converted into a constrained minimization problem with similar results.

IV. SUMMARY AND POLICY IMPLICATIONS

The effectiveness of the catalytic converter technique of abating air pollution depends upon the continued use of unleaded gasoline. It is clear that at the present time, when misfueling is not illegal for the individual, net private gains exist for many motorists from using leaded gasoline. Misfueling can be reduced by making it illegal for the motorist to use leaded gasoline improperly, since the effect of the expected penalty and the increased risk of loss from punishment will reduce and possibly eliminate the private gains.

It should be emphasized that consumers, contrary to the assumptions made in section II, would not operate with full information concerning the relevant choice variables. If a Federal misfueling law is passed, the strategic use of this lack of information on the part of potential misfuelers could be employed to increase the effectiveness of enforcement efforts. A campaign could be mounted emphasizing the maximum penalty involved and considerable publicity could be given to the apprehension of violators. This would tend to raise the subjective probability of arrest and increase the uncertainty of the potential violators. The use of publicity such as this is similar to that often employed by tax authorities in tax evasion cases where, like the area of misfueling, voluntary compliance is very important.

The severity of the penalty is something that can only be speculated about at this point. To be effective, it should exceed the net private benefit from misfueling. To illustrate this point, assume that the private benefit of using leaded gasoline is 10¢ per gallon because of its lower price and superior performance. This would amount to a gain of $1.50 for a fifteen gallon gasoline purchase. If the probability of arrest and conviction is one in one hundred for any particular misfueling, a fine of $150 would be necessary to reduce the expected gain to zero. It would seem that, to be an effective deterrent, misfueling should be dealt with more harshly than routine traffic offenses, yet to maintain a sense of fairness when compared to other offenses, the size of the penalty could not be too high. As mentioned earlier, a policy substituting more severe punishments (which in the case of fines is relatively cheap) for laxer enforcement can be effective only up to a certain point at which the arbitrary nature of the arrangement may cause considerable resentment on the part of the public.

The area of enforcement involves a considerable number of policy questions. The analysis in Section III suggests that (for a given level of penalties) more expenditure should be undertaken as long as the marginal net damage prevented exceeds the extra enforcement and punishment costs. It was also suggested that since the extent of damage from misfueling varies among different areas, enforcement efforts should not be uniform over the whole country. This raises the question of which organization should be used to enforce the law. Since the misfueling law would be a Federal act, it would not be expected that local and state law enforcement organizations would be active in this area. Some Federal organization with central control which could distribute enforcement efforts among different areas in a rational way would be needed. The organization which is charged with monitoring violations by service stations could have its mission expanded to include the observation of motorists as well. An additional possibility which would transfer some of the costs of enforcement on service stations would be to make them liable along with the motorists for misfueling at their stations. This would be similar to underage drinking restrictions where both the seller and the buyer are responsible when an offense occurs.

The techniques for enforcement and their associated costs would depend upon the way the law is written and the legality of various search techniques. A cheap and very effective enforcement technique would be random checks of automobiles on the road in which samples of gasoline would be taken to see if leaded gasoline is being used. This may very well be illegal, however, since motorists would be stopped without any overt evidence that they are violators. If this technique could not be used, then more traditional and somewhat more costly methods such as stationing observers around self-service stations to look for misfuelers could be adopted. It would presumably not require a great deal of skill to identify offenders. Knowledge of the make and year of the automobile and the location of the leaded gasoline supply would be sufficient. As mentioned earlier, making arrests highly visible would accentuate the deterrent effect of the operation. Unlike most other crimes, misfueling has to occur at a completely predictable place, the self-service gasoline pump. Therefore, a rather small number of observers could be very effective in establishing a relatively high probability of arrest.[7]

In summary, once a law banning misfueling by motorists was passed, it could have an almost immediate impact on reducing the misfueling problem. It is expected that enforcement and punishment costs, while not insignificant, would not be of an overwhelming magnitude. Such a law would be even more important if the price differential between leaded and unleaded fuel increases and if shortages develop in unleaded gasoline. The policy also has the great advantage of giving flexibility among the regions of the country based upon each areas' relevant characteristics. This flexibility can be achieved through the allocation of enforcement efforts to the areas where there are the greatest environmental payoffs. One drawback, however, is that to the extent the policy is effective, it may, at least in the short-run, increase the relative scarcity of unleaded gasoline. On balance and assuming the environmental damage caused by misfueling is of a significant magnitude, a Federal law against motorists' misfueling would have a fairly substantial effect with rather limited enforcement costs in a relatively short period of time.

The passage and implementation of such a law should be preceded by the acquisition of data concerning the variation in environmental damage from area to area caused by misfueling, estimates of motorists' evaluation of the differential between leaded and unleaded gasoline and finally, some rough estimate of the response of misfueling violations to various penalties and enforcement measures. These would be very important in the designing of the law and later in its implementation.

FOOTNOTES

1. The following analysis of the decision to engage in illegal activities draws upon the work of Becker, Tullock and Ehrlich.

2. The variance of expected income is given by the formula:

$$\begin{aligned}\mathrm{Var}(I) &= (1-g_m p_a)(g_m I_m + (1-g_m) I_n - E(I))^2 + g_m p_a (g_m I_m + (1-g_m) I_n - Pen - E(I))^2 \\ &= (1-g_m p_a)(g_m p_a Pen)^2 + g_m p_a (-Pen + g_m p_a Pen)^2 \\ &= (1-g_m p_a)(g_m p_a) Pen^2 .\end{aligned}$$

3. This geometric example is constructed for the case where $I_m = 2I_n = Pen$. The very large difference between legal fueling and misfueling is used to make the geometric exposition clearer. In reality, this difference is likely to be much smaller which would mean that more corner solutions with all leaded or all non-leaded use would result as compared to this example. For a similar geometric technique, see Tobin.

4. The question of the weight placed upon the offender's gain is discussed by Becker and by Block and Heineke.

5. The third term of the first equation and the second term of the next equation are, strictly speaking, ambiguous with respect to the sign. This is true because increasing the level of enforcement or the severity of the punishment will not necessarily increase total punishment costs since there will be a reduction in the total number of offenses. This can be framed in terms of the elasticity of misfueling with respect to the probability of arrest or to the severity of punishment. For a derivation of these elasticities in a somewhat different context, see Becker.

6. The costs of using a strategy of a low apprehension rate and a severe punishment are discussed by Schwartz and Tullock.

7. Another enforcement possibility would be to require periodic inspections to determine if the catalytic converter of an automobile is functioning properly. This option is not considered here since it is very similar to the Inspection-Maintenance (INSPMT) strategy which is discussed in other papers relating to the misfueling problem.

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LIST OF SYMBOLS

I_n	consumer's income (both pecuniary and psychic) realized with the exclusive use of non-leaded gasoline. (measured in dollars
I_m	consumer's income (both pecuniary and psychic) realized with the exclusive use of leaded gasoline. (measured in dollars)
g_m	the fraction of a motorist's gasoline usage which involves misfueling
p_a	the probability of arrest and conviction during a certain period if misfueling is practiced exclusively
Pen	the penalty levied against an offender for misfueling (evaluated in dollars)
G_l	the total amount of leaded gasoline used in misfueling
p	the probability of arrest and conviction per unit of misfueling
b_m	net private benefit to the motorist per unit of misfueling
d_e	environmental damage per unit of misfueling
C_e	total cost of enforcement measures
C_p	total cost of punishment activities

ENFORCEMENT COSTS OF FEDERAL LAW AGAINST MISFUELING*

Douglas C. Dacy

It can be argued that misfueling is an anti-social act which might be prevented if there were a law making it a crime and fixing culpability upon the perpetratory. In fact, in some cases enforcement of the Clean Air Act is a federal responsibility, so there is a precedence for federal action against misfueling. In principle, state laws would serve the same purpose and might be more desirable than a federal law in some respects. We consider a federal law because of the greater difficulties in obtaining enactment in 50 separate legislatures, although the analysis applies equally to state laws. The point is that the misfueler should be subject to a certain penalty if it can be proved he has violated the law.

Misfueling arises in the first instance by what is known in the economics literature as the "free rider" phenomenon. Most people want clean air but they also want to maximize their *private* net benefit. If only one person were to misfuel, he could increase his own real purchasing power by buying cheaper leaded gasoline and would also reap the advantage of clean air. He would enjoy a "free ride" if everyone else passed up the temptation to misfuel. The problem arises, of course, because everyone feels the same way: each potential misfueler can rationalize the act as contributing only insignificantly to pollution. However, when everyone misfuels, clean air is

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*For a more detailed analysis that overlaps with that presented here, see J. Fred Giertz, "An Analysis of a Federal Law Against Misfueling by Motorists," this volume.

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severely jeopardized and everyone who values it loses, including the misfuelers. One accepted role of government is to establish rules of conduct for each individual when private actions reduce the social welfare. In the case of misfueling, a government action to cause the potential misfueler to take account of the social costs of his antisocial behavior would seem to be justified. From the government's point of view, the only question is whether the cost of enforcement of antipolution regulations is worth the social benefit the law is intended to provide.

1. METHOD FOR ESTIMATING COST OF ENFORCEMENT

We shall attempt to provide a rough estimate on the cost of enforcement. This estimate depends upon a number of assumptions and should be considered only as a "starting" figure to be adjusted with better assumptions and data when they become available.

The first assumption is that the "average" potential misfueler is economically motivated. He calculates the financial benefit realized through misfueling and will misfuel if the calculated benefit is greater than the expected cost of misfueling. Let B = the monetary benefit from misfueling and E(C) = the expected cost of misfueling. Misfueling is rational when

$$B > E(C) . \qquad (1)$$

The pecuniary benefit from misfueling is easy to calculate. It is the number of gallons used (G) times the price differential (DIF) between leaded and unleaded gasoline.

$$B = G \cdot DIF . \qquad (2)$$

The expected monetary cost (E(C)) of misfueling is equal to the penalty (PEN) if caught in misfueling times the probability of apprehension (P_A).

$$E(C) = P_A \cdot PEN . \qquad (3)$$

The government can make the expected cost any number that it wishes (within reason) by fixing the penalty or the probability of apprehension. P_A depends upon the number of investigators (agents) hired by the government. Suppose the penalty is determined as the cost of the catalytic converter plus some punitive fee, say $50. The size of the fee would be restricted by the size of fees for violations of misdemeanors of equal severity.

To limit misfueling the government could hire just enough agents to raise P_A to some number such that B = E(C). This is found by equating equations (2) and (3) so that

$$P_A^* = G \cdot DIF/PEN \; , \qquad (4)$$

where P_A^* is the probability of apprehension that just deters the "average" potential misfueler from committing the act. Suppose that for each fueling G = 12 gallons, DIF = 5¢, and PEN = $250. Then the single fueling probability of apprehension that just exactly removes all expected reward for misfueling is

$$P_A^* = 12 \times \$.05/\$250 = .0024 \; .$$

Assume also that misfueling is a random event at the "typical" station. Its expected occurrence at any minute of the day is equal to that at all other minutes. Now suppose there is a "typical" self-service station that is open for business 12 hours a day for seven days a week. If an agent were to spend all day at one station he would apprehend all violators. P_A at that station would be 1. To set an average P_A^* at .0024, as in the above example, no agent would be placed at 416 stations for every one station where there was full surveillance. Thus, the weighted average P_A would be $\frac{1 \times 1 + 416 \times 0}{417} = .0024$ or, in general

$$P_A^* = S_A/TS \; , \qquad (5)$$

where S_A = stations with agents

TS = total stations

and the number of agents necessary would be:

$$\text{No. of Agents (unadjusted)} = S_A = P_A^* \cdot TS \ . \qquad (6)$$

Of course, the same result could be obtained by assuming that misfueling is a random event at each station. Its expected occurrence at any minute of the day is equal to that at all other minutes. In this presentation agents would visit numerous stations on a random basis throughout the day. In any case, the number of agents required to fix a desired probability of apprehension is that probability times the total number of stations where misfueling easily could take place without the cooperation of an attendant (opportunity stations).

The surveillance week is approximately 84 hours. However, the hired agents probably would work 40 hour weeks. Also, agents would not want to spend long periods of time at any one station and the travel time between stations would consume part of the surveillance time. In order to obtain the desired P_A, therefore, more agents would be required. If surveillance time per week is 84 hours, agents work 40 hours per week, and they spend 20 percent of their time traveling from station to station the number of agents required would be 1.2 x 84/40 = 2.5 times the number calculated by Equation (6). Let α be the adjustment factor just described, then

$$\text{No. of Agents (adjusted)} = \alpha \cdot P_A^* \cdot TS \ . \qquad (7)$$

2. ESTIMATE OF THE COST OF ENFORCEMENT

As in the previous example we assume that the probability of apprehension required to deter the "average" potential misfueler is .0024. We shall also assume that the adjustment factor (α) is 2.5. To compute the required number of agents we need an estimate of the number of opportunity stations where a potential misfueler can handle the gasoline hose. The approximate numbers for April 1979 are*

	Percent of Total	Total Number
Self-service stations	27	45,900
Split-island stations	38	64,600
Total "Opportunity Stations"	65	110,500

The total "opportunity stations" was 65 percent of the number of service stations.

No. of Agents (adjusted) = 2.5 x .0024 x 110,500 = 663.

If each agent were paid $20,000 and overhead costs plus the annualized value of capital costs were 100 percent of salary, the total enforcement costs would be $26,520,000. This figure is suggested here to be the roughest kind of estimate. One can easily revise it in line with alternative assumptions.

3. FURTHER CONSIDERATIONS

Obviously, employing a force of about 700 agents of which only about half would be on the job at any time would not prevent misfueling totally. The efficiency of deterence would depend on a number of factors that have not been taken into account in our formal analysis. Some of these are operational matters--the manner in which the enforcement agents would be employed--and they can be grouped under two headings as follows:

a. Factors Leading to Improved Effectiveness of Enforcement

(1) Agents could be employed optimally rather than randomly. In general they would spend more time at larger stations and less time at smaller stations.

(2) Agents most effectively would be employed in large urban areas and only minimum effort would be made to enforce the law in rural areas.

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*Data from Lundberg Letter, April 27, 1979.

b. Factors Leading to Reduced Effectiveness of Enforcement

(1) The fact that agents would not work around the clock would encourage misfuelers to change their temporal habits of buying gasoline.

(2) Misfueling would be encouraged in regions where enforcement was lax.

It seems that every move by the government to improve efficiency of enforcement could lead to countermodes by potential misfuelers to avoid apprehension. While this is a valid statement in principle, we place very little practical importance on it. The economic benefits are too low to encourage huge efforts on the part of potential misfuelers to circumvent the law.

Nevertheless, some misfueling could continue even in the context of our formal model. How much would take place and how much additional effort (cost) would be required to prevent it?

Recall that our "rational" misfueler would misfuel so long as the calculated economic benefits exceeded the expected cost of misfueling. The calculated benefits depend upon the number of gallons taken per fueling. Our estimate was based on an "average" number of gallons per fueling. Yet, the number probably varies considerably between people. Anybody who makes fewer fueling stops and consumed more gallons per fueling than the average would realize greater benefits than average while subject to the same expected costs. If such a person were a "rational" misfueler, he would not be deterred by the probability of apprehension computed for the average. If the distribution of motorists by number of gallons taken per fueling were normal, only half the potential misfuelers would be deterred by the kind of "rational" calculation we have assumed. However, the distribution undoubtedly would not be normally distributed around some average such as twelve gallons. Many tanks hold only 13-17 gallons.

In any event the cost of the enforcement program is linear in the desired probability of apprehension. The distribution of expected benefits would not be linear. Therefore, any effort to apprehend, say an additional 10 percent misfuelers would cost more than an additional 10 percent. Or to put the matter in perspective, if 75 percent of motorists use twelve or less gallons per fueling, and 25 percent use more than 12 gallons, the total cost of the program would have to be doubled to deter the last 1/3 of the misfuelers under the assumptions we have made.

A federal law against misfueling probably would be partially effective even if it were not enforced. With such a law the concept of a "rational" misfueler is somewhat artificial. Some persons just on the verge of misfueling undoubtedly would pass up the chance to misfuel if they knew they were breaking a law. Rationality encompasses more than maximizing economic benefit. Another way to look at the same effect is to note that for people who feel guilty in breaking even minor laws, the calculated benefit (B) would have to exceed the expected cost (E(C)) by some factor X because the total cost of misfueling, for those persons, would be greater than the expected value of the penalty. With this consideration the methodology described above would yield a maximum cost of enforcement rather than the expected cost.

Whether a federal law is a proper approach to fueling enforcement depends upon the value one places upon the reduction in air pollution in comparison to the costs of enforcement. We do not know how to value the benefits, therefore, we cannot make a recommendation. In our opinion the cost of enforcement of a federal law appears to be higher than those associated with other options that will achieve at least the same benefits in terms of pollution abatement. One such option is inspection and maintenance programs. Those appear to be more cost-effective than enforcement of a federal law and, if that is true, the option of a federal law should be rejected.

NOTE ON ESTIMATING POTENTIAL CHANGES IN GASOLINE PRODUCTION DUE TO CHANGES IN APPLICATION OF ADDITIVES

Douglas C. Dacy

The impact on gasoline production from permitting the use of MMT in unleaded gasoline, or from the greater application of lead in leaded gasoline, depends upon many variables. Among them are type of crude used, size of refinery, technology, government regulations, and economic variables such as prices of all the joint products. The reported numbers on "gasoline savings" or "crude savings" due to higher concentrations of octane boosters vary considerably and, at best, are ambiguous. For example, it has been reported in the press that the "oil industry claims" the use of MMT will increase availability of *unleaded* gasoline by 340,000 barrels per day.* In a paper prepared by two analysts at the Ethyl Corporation, the authors state: "Various refiners have estimated that the inability to use MMT (at 1/16 g Mn/gallon) will reduce total gasoline production by 4 percent to 8 percent during the next several years."† These two statements, both attributed to the oil industry, appear to be inconsistent if not contradictory. The first refers to *unleaded* gasoline, the other to *total* gasoline.

When different analysts are questioned about such inconsistencies typical responses are: "Gasoline production is very complicated" or "One needs a large computer model to decide the

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*Larry Kramer, "EPS Suspends Rule Barring Gas Additive," *Washington Post*, May 31, 1979, C1.

†George H. Unzelman and George W. Michalski, "Octane Improvement Economics - Anti-knocks and Alternatives," NPRA Paper AM-79-46, presented at the 1979 NPRA Meeting, March 1979, pp. 5-6.

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right answer." Both responses, undoubtedly, are correct. Neither is helpful. The purpose of this note is to outline and defend several very simple methods for deriving an estimate of the amount that gasoline production could be increased when there is a change in the quantity of an octane-boosting additive. The derived estimates are only approximations: While they are not intended to convey exactness, they will be useful for judging the reasonableness of other estimates.

Method 1: Octane Pool Method

This method assumes that the U.S. refining process yields, at any given time, a known clear octane pool which can be distributed between leaded and unleaded gasoline. The actual proportions depend upon economic considerations; however, these will be ignored in this narrowly technical analysis. Unleaded gasoline has a high clear octane whereas leaded gasoline combines lead alkyl antiknock with a relatively low clear octane to obtain the desired octane number. Using an additive such as MMT to boost octane in unleaded gasoline permits refiners to reduce the clear pool requirement for unleaded gasoline *but does not affect the total amount of gasoline available.* It allows refiners to increase the proportion of total gasoline production in unleaded gasoline while reducing the proportion in leaded gasoline.

The following method can be used to calculate the maximum possible shift:

Let

p = percent of clear pool used in leaded gasoline
CRONL = clear research octane number of leaded gasoline
CRONU = clear research octane number of unleaded gasoline
CRONTP = clear research octane number of total pool

At any time the following identity holds:

$$p.CRONL + (1-p)\ CRONU = CRONTP\ .$$

The purpose of using MMT is to lower the required value of CRONU. To produce additional unleaded gasoline while maintaining the above identity with a lower CRONU (1-p) must rise and p must fall. Since CRONL, CRONU, and CRONTP are predetermined, it is a simple matter to calculate p. The difference between p with and without MMT is a measure of the potential for increasing production of unleaded gasoline at the expense of leaded gasoline.

According to data published by Ethyl Corporation researchers the values of the variables defined above are:

	Before Using MMT*	After Using MMT
CRONL	83.0	83.0
CRONU	93.5	92.3†
CRONTP	86.7	86.7
p	.645	?

If refiners were to use 1/32 gram MMT/gallon of unleaded gasoline the required clear pool could be reduced by 1.2 RON** or from 93.5 to 92.3 as shown above. Assuming no change in the application of lead in leaded gasoline, CRONL would remain at 83. With this information it is possible to complute a new value for p. Call it p'.

$$p'.CRONL + (1-p')CRONU = CRONTP$$
$$83.0\ p' + 92.3\ (1-p')CRONU = 86.7$$
$$p' = .60$$
$$(1-p') = .40$$

and p-p' = .645 - .600 = .045.

By allowing the application of MMT a given total octane pool could support an increase in unleaded gasoline production

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*Unzelman and Michalski, *Idem.*, Table A-1, p. 21.

†See text immediately following.

**See Figure 1.

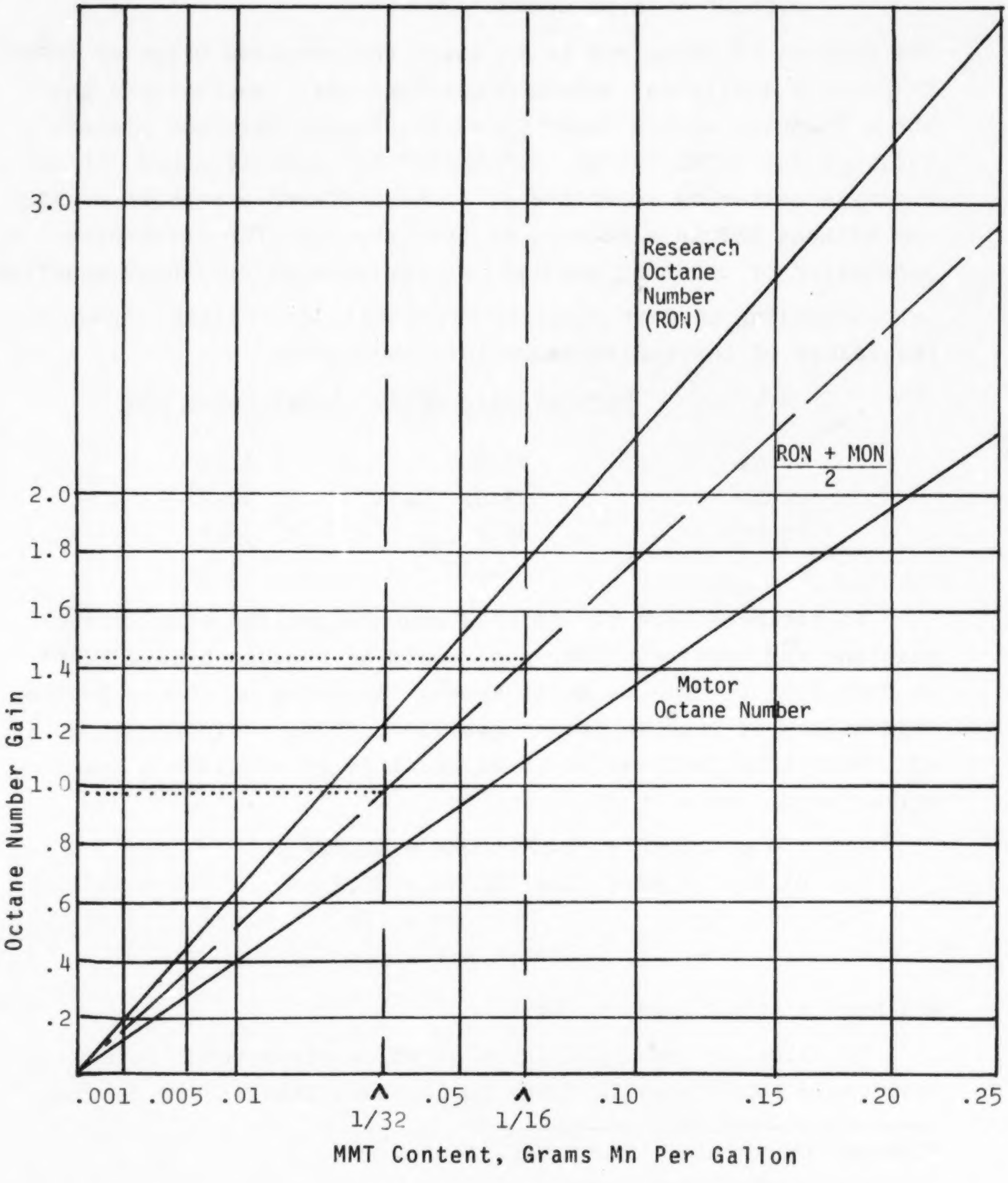

Figure 1. AVERAGE OCTANE GAINS FROM USING MMT

from 35.5 percent to 40.0 percent of total gasoline production, or an expansion of 4.5 percent.* This figure translates into daily production:

$$\Delta \text{ Unleaded} = .045 \times 7{,}500{,}000 \text{ b/d} = 338{,}000 \text{ b/d} .$$

We note that this estimate, derived from the simple method outlined, is identical with the Ethyl Corporation's estimate and similar to other quotes attributed to the petroleum industry.

We stress that the above estimate is a *maximum*, assuming no constraints, and not an *expected value*. In fact, there is a major constraint: At present, and for at least a future period of eighteen months, the manufacturers of MMT cannot produce enough of the additive to supply 1/32 gram/gallon for all unleaded gasoline and still meet the demand for other uses.† Given current production capacity, additional production of MMT would be sufficient to supply about 2/3** of the MMT for all unleaded gasoline if the application were 1/32 gram/gallon. Thus, if used in the amount of 1/32 gram/gallon, the capacity constraint would reduce the maximum additional unleaded gasoline production to 225,000 b/d. This constrained maximum is a more valid figure than the unconstrained maximum frequently quoted.

The constrained maximum assuming application of 1/32 gram/gallon is not optimal. Given the capacity constraint it would be better to use 1/48 gram/gallon in all unleaded gasoline for the octane response to MMT is not linear. If MMT use were optimized, the constrained maximum would be 240,000 b/d.††

Whether the production of unleaded gasoline would actually respond to MMT usage by the constrained maximum is questionable.

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*The figure is virtually the same when the calculation is based on (R+M)/2 rather than RON.

†Information supplied by Mr. Howard Hesselberg, Vice President of the Ethyl Corporation.

***Ibid.*

††Application of 1/48 gram/gallon permits a reduction in the clear pool of unleaded gasoline by .94 RON.

The answer depends upon some important economic conditions. In the present situation of a general shortage of gasoline in which the price of leaded gasoline has risen faster than that for unleaded gasoline the incentive to shift production away from leaded gasoline has been greatly diminished. Thus, if the present conditions were to persist, one would guess that the technical maximum would not even closely be realized. Of course, if the shortage of leaded gasoline were to disappear in the intermediate-term, the technical maximum would take on additional credibility. However, even in that situation it would not seem wise to use an absolute maximum for the purpose of policy analysis.

In the intermediate-term, say after MMT production could be increased, the case for permitting the use of MMT in unleaded gasoline would be improved. There are two reasons for this statement: (1) Removal of the constraint improves the ability of the MMT policy decision to increase the production of unleaded gasoline; and (2) the potential supply response depends critically upon the proportion of the total gasoline pool in leaded production. If leaded production were 50 percent, as it is likely to be in 1981, use of 1/32 gram Mn/gallon of gasoline could permit a shift of 525,000 b/d to unleaded gasoline. The greater the opportunity for using MMT (the greater the share of unleaded gasoline) the greater is its technical potential for increasing production of unleaded gasoline.

A Non-Methodological Digression

In the quotation on page 1 of this note, Ethyl analysts attributed to "various refiners" the estimate that prohibiting the use of MMT in unleaded gasoline would reduce total gasoline production by 4 to 8 percent "during the next several years." We do not know the exact basis for such a statement but assume that the figures quoted were outputs of refinery models using the best guesses about future economic conditions available to the analysts who operate the refinery models. In other words, we assume that the computer runs on which the statement was based took advantage of what the analysts considered realistic assumptions. If so, their estimates can be scaled in such a way to yield an estimate of what might happen to unleaded gasoline production in consequence of the the removal of the ban on MMT.

Four to eight percent of total gasoline production translates to 300-600,000 b/d. For simplicity we take the average, 450,000 b/d. The 4-8 percent range was predicated on the usage of MMT in concentrations of 1/16 gram/gallon. At concentrations of 1/32 gram/gallon the octane boosting capability of MMT is approximately 68 percent the octane boosting capability if used in concentrations of 1/16 gram/gallon. Making a simple adjustment to correspond with 1/32 gram/gallon we calculate that 300,000 b/d extra gasoline might be produced. Finally, and in the absence of concrete information, we assume that only 40 percent of the total increase would go to unleaded production and, therefore, unleaded gasoline might increase by 120,000 b/d.

This calculation cannot be verified. It is based on a number of implicit assumptions. One might be that refiners would increase the production of gasoline at the expense of middle distilates if they were allowed to use MMT as an additive to unleaded gasoline.

Method 2. Crude Oil Savings Method

As a result of using MMT the clear octane requirement in unleaded gasoline would be lowered. Thus, the "severity" of refining could be reduced allowing a given volume of outputs to be maintained with a smaller volume throughput of crude oil. In the *crude oil saving method,* all variables in the refinery process are assumed to be held constant with the exception of the additive and the partial effect on gasoline production is computed. In this method the crude savings can be turned into gasoline production and so additional production can be obtained rather than a shift in production between leaded and unleaded gasoline.

For the purpose of description assume the basic estimating equation is:

$$g = f(O,M,T,R,C_i,P_i,A,X_i) \quad . \tag{1}$$

The definitions of the variables are:

g = total production of gasoline
O = total throughput of crude oil
M = mix of crude, i.e., weighted average of all types of crude being used
T = refinery technology
R = government regulations
C_i = vector of costs of all joint products of the refinery process
P_i = vector of market prices of all joint products of refinery process
A = concentration of octane-boosting additives in grams per gallon
X_i = vector of all other factors affecting gasoline production .

The values of the arguments in the above equation frequently change and, therefore, g is not stable. In attempting to estimate Δg as a function of ΔA, it is important to hold all other inputs constant. One learns very little about the influence of A on g if R is allowed to change at the same time. Conceptually, to find the pure effect of additives on gasoline production it is necessary to hold all other inputs constant. Precisely what is needed to estimate the effect of ΔA on Δg is to rid the estimation of all its "complexity," i.e., to assume that all inputs other than A do not change. In essence, we wish to estimate $\partial g/\partial A$.

Michalski and Unzelman have derived a relationship between "energy penalty" and clear octane number.* The relationship is reproduced as Figure 2. The energy penalty is the number of barrels of crude per 100 barrels of gasoline that is sacrificed by varying the clear octane number in gasoline. For example, at 83.7 clear octane, the average from the remaining process, no energy penalty is experienced. However, if we wished to raise the clear octane number to 86, 2 additional bbl of crude per 100 bbl of gasoline would be required. If 1,000 bbl of crude were required to produce 500 bbl of gasoline with clear octane number, (R+M)/2, of 83.7, raising the octane number to 86 would require 1010 bbl of crude. In this example, the crude input would be increased by 1 percent to produce 2.3 additional octane numbers. Conversely, reducing the octane number from 86 to 83.7 would result in a saving of 10 bbl crude, or 1 percent.

The information contained in Figure 2 and supported by various simulations in Figure 3 pertains to "energy penalty" but does not directly answer the related question: How much can gasoline production be extended by use of octane-boosting additives for a given throughput of crude oil? This latter question is the important one in a period of crude oil scarcity or when restrictions are placed on oil imports into the U.S. To answer this question it is necessary to make a critical assumption. That assumption is:

> Crude oil savings realized by lowering the required clear octane pool made possible by octane boosters can be transformed into an equal volumetric gain in gasoline.

This assumption might seem extreme but it is only consistent with with the requirement of holding all other arguments constant. Under this assumption, for example, the other major refinery

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*G.W. Michalski and G.H. Unzelman, *Effective Use of Antiknocks During the 1980s*, Preprint No. 22-79, American Petroleum Institute, Washington, D.C., May 1975, p. 13.

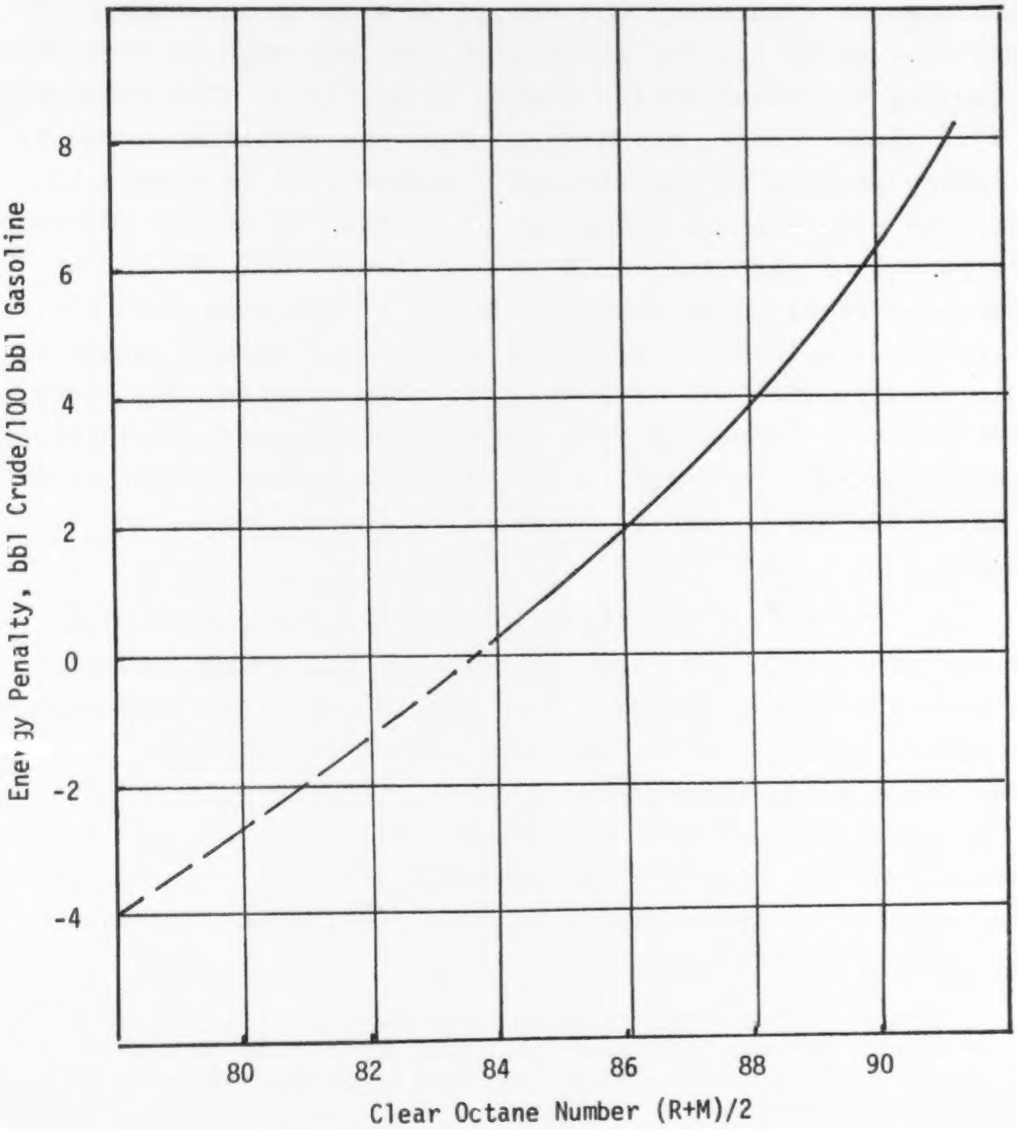

Figure 2. REFINERY ENERGY PENALTY FOR PRODUCING CLEAR OCTANE NUMBERS

Source: G.W. Michalski and G.H. Unzelman, *Effective Use of Antiknocks During the 1980s,* Preprint No. 22-79, American Petroleum Institute, Washington, D.C., May 1979.

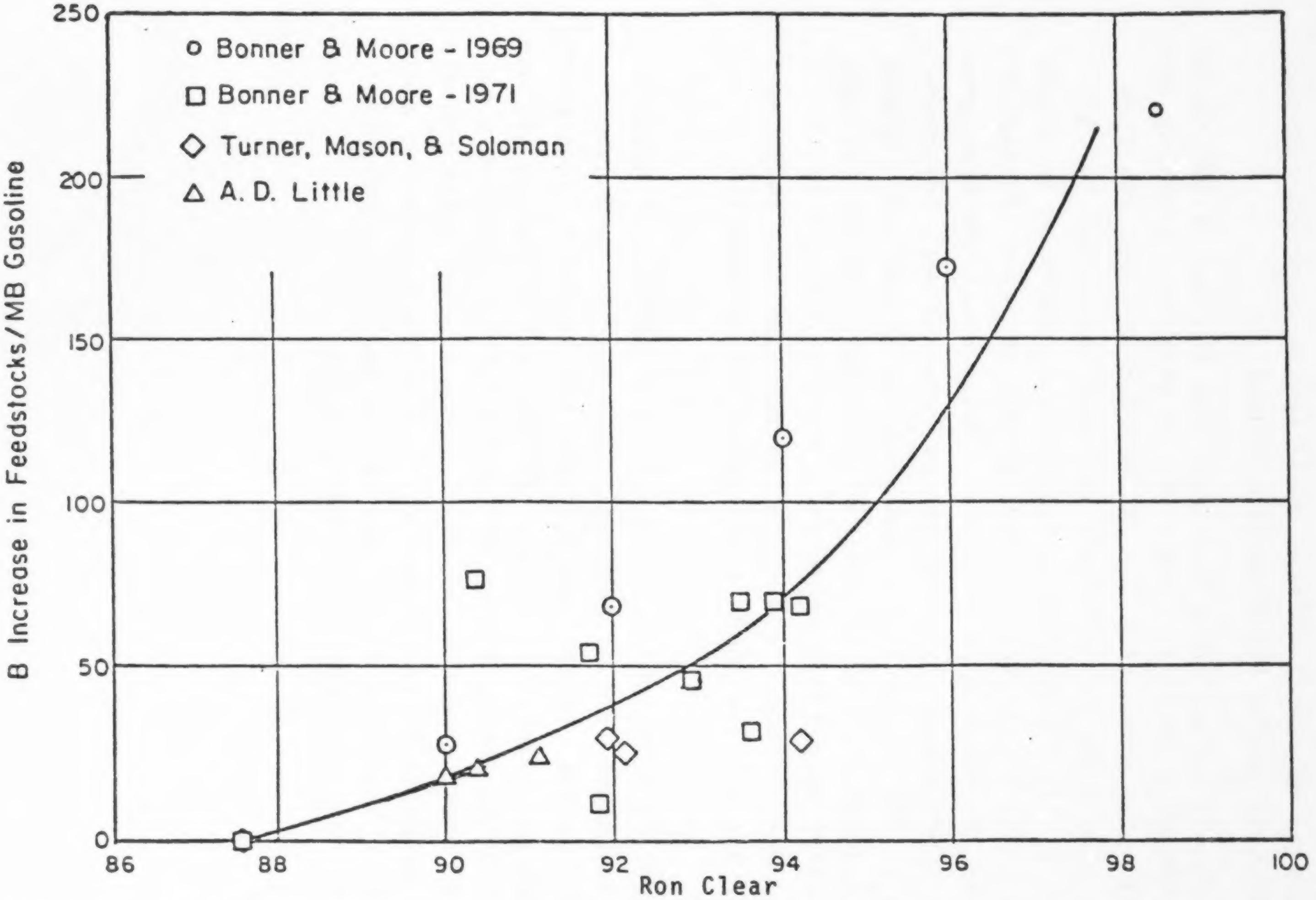

Figure 3. ADDITIONAL FEEDSTOCK CONSUMPTION ASSOCIATED WITH REMOVING LEAD FROM GASOLINE

Source: W. Sheppard, et. al., *The Economic Impact of Environmental Regulations on the Petroleum Industry*, Phase II Study, Battelle, Columbus, Ohio, June 1976, p. v-119.

outputs such as middle distilates would remain constant although their volumetric ratios would decline slightly.

In concentrations of 1/32 gram/gallon the use of MMT would permit a reduction in clear octane of .92 (R+M)/2. Assuming that unleaded gasoline production were 40 percent of total gasoline production, the clear pool for all gasoline could fall by .37 octane (.92 x .4). According to Figure 2, a reduction in octane from 84 to 83.63 would yield a crude saving of about 1/3 barrel of crude per 100 barrels of gasoline. Since total gasoline production is approximately 7.5 million barrels per day, the crude saving due to MMT use would be approximately 25,000 b/d. Almost all of this could be used to make unleaded gasoline without sacrificing leaded gasoline production. Thus, 25,000 b/d is the approximate maximum additional unleaded gasoline that could be produced by using MMT without sacrificing leaded gasoline production.

In terms of Equation (1) this figure is $\partial g/\partial A$. It assumes all other variables remain constant. This may not be a good assumption. In the special case of MMT, the vector C_1 undoubtedly would change as a result of removal of the restriction on its use. Cost of producing gasoline with MMT would decline relatively to the costs of other products for which there were no prior restrictions. In response to the change in C, gasoline production would rise further. Thus, the total increase in gasoline production would be greater than that indicated by $\partial g/\partial A$.